# An Inquiry Into Virtual Materiality

by

Joss Kingdom Moo-Young

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# Thesis Examination Information

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An oral defense of this thesis took place on August 9, 2023 in front of the following examining committee:

**Examining Committee:**

| | |
|---|---|
| Chair of Examining Committee | Dr. Miguel Vargas Martin |
| Research Supervisor | Dr. Andrew Hogue |
| Co-Research Supervisor | Veronika Szkudlarek |
| Examining Committee Member | Dr. Bill Kapralos |
| Thesis Examiner | Dr. Patrick Hung |

The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

# Abstract

"We shape our tools, and thereafter they shape us,"—this Mcluhanism demands that when we create, we do so thoughtfully. This thesis examines artists' relation to VR tools for 3D shape modelling and their needs regarding VR creativity. A new interaction model is presented for sculpting in VR featuring physicalized tools which interact with mass-conserving voxel 'clay' material. The model is included in a pilot study comparing three sculpting methods using within-subject trials and a focus group with eight artists. Statistical analysis of questionnaire responses measuring six aspects of Creativity Support Index revealed that the new model was not favoured over industry-level software. Thematic analysis of feedback and observations characterized artists' experiences in VR sculpting. The analyses suggest future VR sculpting tools should improve 1. Haptic Response, including Pseudo-Haptic techniques, and 2. Kinetic Response, leveraging the emotive nuance in the body, and respecting VR as an alternative reality.

**Keywords:** Shape Modelling; Digital Sculpting; Human-Computer Interaction; Creativity Support; Virtual Reality

# Author's Declaration

I hereby declare that this thesis consists of original work of which I have authored. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I authorize the University of Ontario Institute of Technology (Ontario Tech University) to lend this thesis to other institutions or individuals for the purpose of scholarly research. I further authorize University of Ontario Institute of Technology (Ontario Tech University) to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research. I understand that my thesis will be made electronically available to the public. The research work in this thesis that was performed in compliance with the regulations of Research Ethics Board under REB Certificate number 14092.

Joss Kingdom Moo-Young

# Statement of Contributions

My supervisors Dr. Andrew Hogue and Veronika Szkudlarek determined the research topic of applying physics simulation to materials in VR. I researched and explored options within the topic, designed and developed the software, and created some of the 3D models used in the application. Part of the work described in Chapters 1-3 have been published in a working paper as:

J. K. Moo-Young, A. Hogue, and V. Szkudlarek, “Virtual Materiality: Realistic Clay Sculpting in VR,” in Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play, ser. CHI PLAY ’21, New York, NY, USA: Association for Computing Machinery, Oct. 2021, pp. 105–110, isbn: 978-1-4503-8356-1. doi: 10.1145/3450337.3483475. [Online]. Available: https://doi.org/10.1145/3450337.3483475.

This thesis constitutes the continuation and succession of that publication. I designed and conducted the study, analyzed the data, wrote the manuscript, and edited it with the aid of guidance and feedback. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others.

# Acknowledgements

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# List of Figures

# List of Abbreviations

**AR** Augmented Reality.

**CAD** Computer-Aided Design.

**CFD** Computational Fluid Dynamics.

**CSG** Constructive Solid Geometry.

**CSI** Creativity Support Index.

**DoF** Degrees of Freedom.

**FEM** Finite Element Method.

**GUI** Graphical User Interface.

**HCD** Human-Centered Design.

**HMD** Head-Mounted Display.

**IVE** Immersive Virtual Environment.

**MR** Mixed Reality.

**NURBS** Non-Uniform Rational B-Splines.

**OSHF** Optically Simulated Haptic Feedback.

**PDE** Partial Differential Equation.

**SDF** Signed Distance Field.

**SDK** Software Development Kit.

**VR** Virtual Reality.

**WIMP** Windows Icon Menu Pointer.

**XR** Extended Reality.

# Contents

# Chapter 1

# Introduction

In 1967, John M. Culkin, known to the world as the father of media studies in American education, published an article introducing the writings of his Canadian friend and now legendary figure in media studies, Marshall McLuhan [1]. “We shape our tools and thereafter they shape us. These extensions of our senses begin to interact with our senses. These media become a massage,” Culkin writes, describing the bidirectional relationship between what humans use and what humans are. The “massage” refers to the way different forms of media massage our senses, and references the title of McLuhan’s then contemporary book: *The Medium is the Massage* [2], an intentionally typographically frustrating play on his own famously thought-provoking statement “The Medium is the Message”. In the world of computer science research, we design and build electronics, machines, paradigms, algorithms, and complex interconnected systems that help humans think, learn, create, communicate, congregate, and play. We strive to make computing better, which, ultimately, should be contextualized in how we can make human lives better. In this pursuit, we shape our tools. However, we must not forget to consider how our tools shape us. In this thesis, I contribute a small part of the process of evaluating, guiding, and shaping our digital tools. Specifically, simulating artistic materials in Virtual Reality (VR). I invite you to use this text to inspire you to consider the qualities and implications of materiality in virtuality.

## 1.1 Implementation Shows Through

A computer programmer is an expert in interacting with computers. When a computer programmer writes code, they consider their audience: a compiler or interpreter. They think about data structures, the storage and flow of information, the specific hardware capabilities, strengths, and weaknesses of their target platforms. They form their messages with these considerations in mind, so the computer will execute the right instructions at the right time, as efficiently as possible. When the computer responds to their actions, the programmer knows how to read the messages and respond appropriately. As a result of these kinds of interactions, the programmer changes. Of course, the programmer is probably creating an application that will be used by a non-programmer. So, that programmer, or their colleagues, must build a front-end facade to interface with the end-user in a more human way. These conventions (e.g Fig. 1.1) attempt to mask what Lev Manovich called the "computer layer," [3] and to bring interactions closer in form to those of the "culture layer". However, as Manovich puts it, "*...the computer layer and the culture layer influence each other. To use another concept from new media, we can say they are being composited together.*" The underlying implementation always shows through.

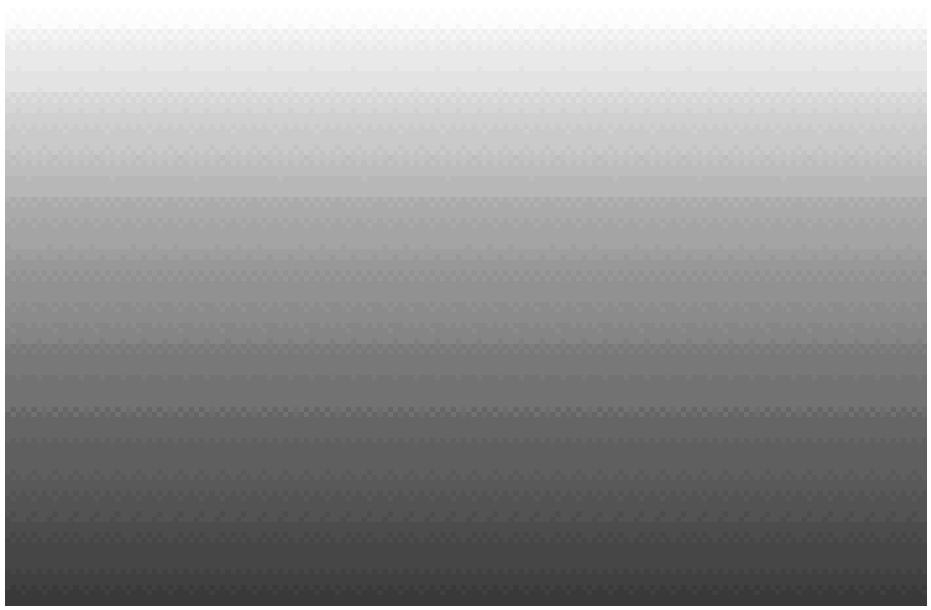


Figure 1.1: Banding effect visible in digital color gradients caused by discrete pixel color data (more visible at lower bit depth representations). A Dithering effect was used to better hide the banding. Built-in dithering is not typically an effect expected as part of creating a color gradient–it is an algorithmic technique by programmers to hide the way computers manage color information and bring it closer to human expectations. This is an example of where the underlying implementation shows through.

Consider the case of a familiar class of computer application, the Raster Graphics Editor, more commonly known by examples such as MacPaint in 1984, or since 1985, Microsoft Paint. As the metaphorical name implies, Microsoft Paint is for some kind of digital version of painting. Its Paint Bucket tool (Fig. 1.2) will fill all adjacent pixels of the same color value with the user's newly selected color value. Contrast this with a real paint bucket in the real hands of a real painter. A real paint bucket can be filled with paint and slowly dumped on a taped-up surface, where it may behave in a way somewhat analogous to Microsoft's Paint Bucket tool. However, a real paint bucket can also produce many other effects through different techniques. You can throw paint from it to create splashes. You can use its circular base as a stencil or stamp. If you need to reach a high shelf, it becomes a stepladder. These are not things the Microsoft Paint Bucket tool can do, nor things we expect from it, because the Microsoft Paint Bucket tool is really an operation. The name ‘Paint bucket’ is part of the user-friendly facade, but the underlying structure of pixels, 2D arrays, RGB color values and the like force users to think in specific ways. If we want a different effect such as *splatter* or *stamp*, we must select the specific operation we want first, select some parameters (e.g. location on the screen, color, opacity), then signal to execute that operation. The Raster Graphics Editor edits discrete digital values in arrays of red, green, blue, and alpha channels, which are sent to computer monitors to emit light of different colors. The program constitutes the ways it can be manipulated, and the data structure constitutes the ‘materials’ that make up its ‘paint’. In this way, *Pixels on Microsoft Paint* can be considered a medium, bearing its own particular tools, materials, processes, artifacts, and modes of viewing.

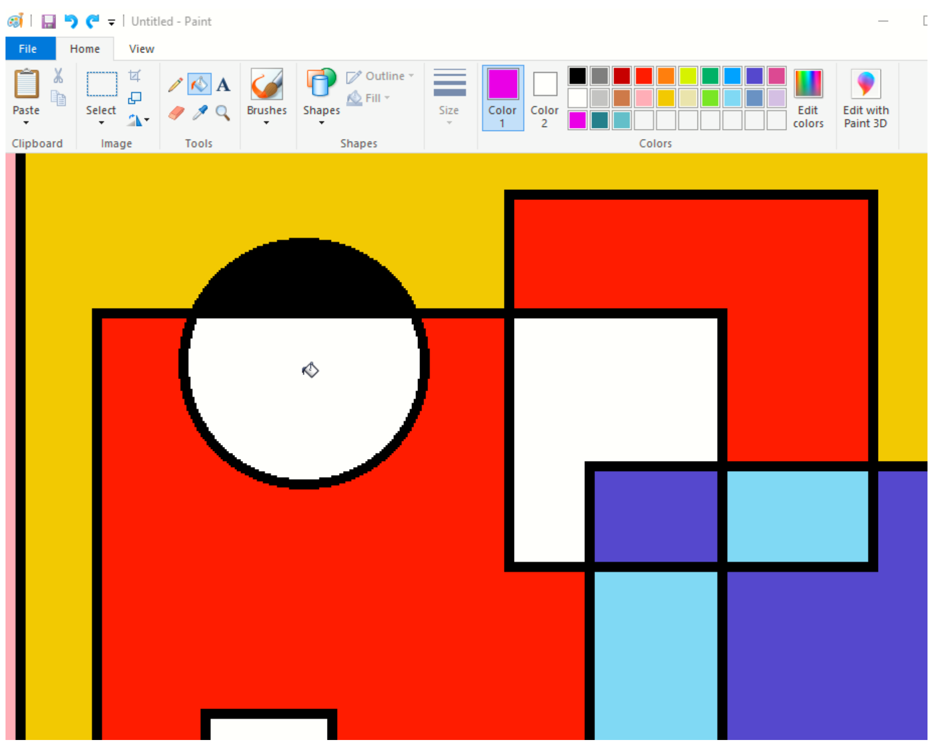



Figure 1.2: Paint Bucket Tool as seen in Microsoft Paint. ‘Paint Bucket’ here is a metaphor, like the folders on the desktop of a computer running the Windows operating system. It has no physical body. It contains no liquid paint. It cannot be held in the hands—but in VR, this is possible.

## 1.2 The Material is the Matter

All artists adapt their creative process to the nature of their tools and materials. Historically, many artists have been recognized as seminal leaders in their field precisely due to their unique understanding and manipulations of a material. Edgard Degas' pioneering impressionistic use of pastels, Jackson Pollock's Action "drip" Paintings, or Louise Bourgeois' subconsiously anthropomorphic sculptures. Similarly, contemporary digital art like Peter Burr's patterned labyrinthine abstractions, Olia Lialina's sprawling HTML net art, or Cory Arcangel's mutilated machines draw inspiration from, and reside inside, the computer world with all its own artifacts and defects. Increasingly, artists are thinking between digital and physical, applying the rules and perspectives of a computer in physical works. Reality-bending technologies like 3D scanning and Virtual Reality (VR) offer new perspectives that creative minds like Rachel Rossin (Fig. 1.3) use to collide our physical lived experience with alternative realities. Digital artists adapt their thinking to support the laws of computer programs. They find that the digital 'law of backface culling' makes seeing through slices of shelled surfaces a natural occurrence (Fig. 1.4). They find that digital objects freely intersect and overlap. The fundamental particles of digital space are the voxel, or the pixel, or the triangle, or bits. The rules and artifacts of the digital 'materials' form media all their own, affecting the way we express and interpret messages. Marshall McLuhan's assertion that *the medium is the message* says our means of communication themselves (not only the content) shape our behaviours and perspectives. Painters and sculptors communicate through materials. Acrylic on canvas, oil on wood. Marble. Plaster. Clay. An artist's medium is described in terms of materials, so we must pay careful attention to the matter which our digital realities are 'made of', and how people interact with them. The material is the matter.

Figure 1.3: Two physical works by Rachel Rossin inspired by digital imagery. *Oranges with Horizon*, 2017 (background) and *After Crybaby*, 2017 (foreground). Artists like Rossin show us the bidirectional nature of inspiration across physical and digital realities–that our tools shape us.

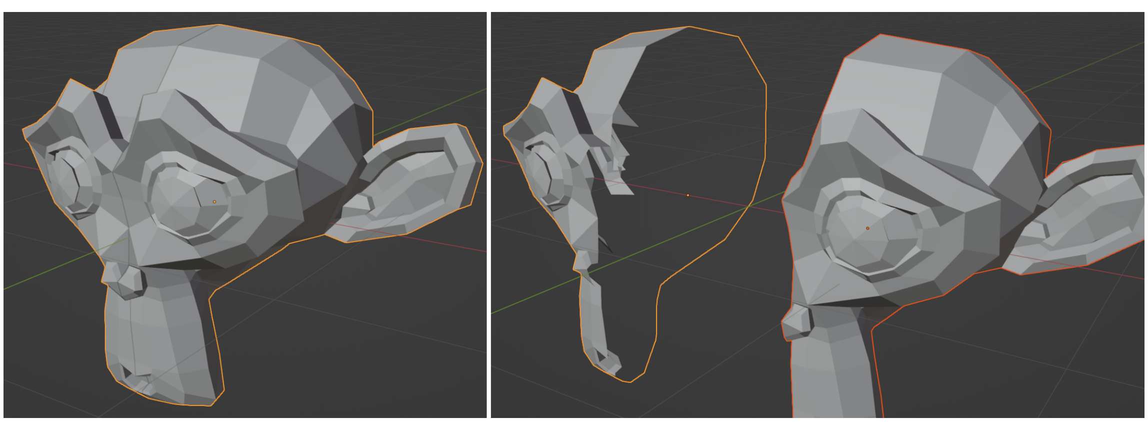


Figure 1.4: Backface culling, the removal of inside faces of geometry before rendering, is both a product of technical optimization and a unique feature of digital space that may be interpreted in unique ways by those who do not see it in terms of graphics API settings and vertex winding orders.

## 1.3 Shape Modelling

In the modern world of digital creativity, there are many choices of ways to create 3D shapes, which often come with different data representations and different ways of thinking about them. The common types of 3D shape modelling programs in use can be categorized by the following: parametric, polygonal, sketching, and sculpting. The most common data representations for 3D shape modelling fall into three categories: *features*, *polygons*, and *voxels*.

### 1.3.1 Parametric Modelling

Parametric modelling allows creators to define a shape by its *features*. A digital model made of *features* is defined by systems of equations or series of operations. This broad classification of "parametric" is being used to encapsulate many specific techniques and data representations that share the commonality of retroactively editable parameters, including Constructive Solid Geometry (CSG) operations [4], Non-Uniform Rational B-Splines (NURBS) [5], subdivision surfaces [6], and Coons Patches [7]. In some tools, the initial conditions and the operations needed to construct the final shape are stored themselves as part of the data model, like an instruction booklet for its re-creation. If the entire history of the operations is saved, as in some programs like Autodesk Fusion 360 [8], then this workflow is non-destructive, meaning that no data about previous versions of the shape are lost when making changes. One may go back in time and change the way they originally cut a piece, or the length of an extrusion. Models created this way can easily have precise measurements changed at any part in the process. This type of modelling is used in Computer-Aided Design (CAD) for engineering, product design, and architecture for its precision and refactorability (Fig. 1.5). However, this mode of creation suffers from inflexibility if a designer wishes to modify specific parts of the shape directly, rather than first translating it into features, constraints, and parameters. This translation requirement is not ideal for the human-intuitive artistic process. One does not simply mould a mathematical function in any way they like without first being forced to think like a mathematician. Known inflexibilities yet present in parametric models used in the field increase the 'cost of change' or force architects to 'start all over again' [9]. The focus on aggregation of features and constraints makes it possible to *overconstrain* a design. Thus, it requires some level of planning about the features ahead of time, which can make it difficult to explore multiple vastly different designs within a parametric modelling context. In practice, the initial exploration can be done by the much more flexible and much less premeditated methods of creation, like sketching. Once a model is constructed, some parameters can be edited, but large fundamental changes still require starting over.

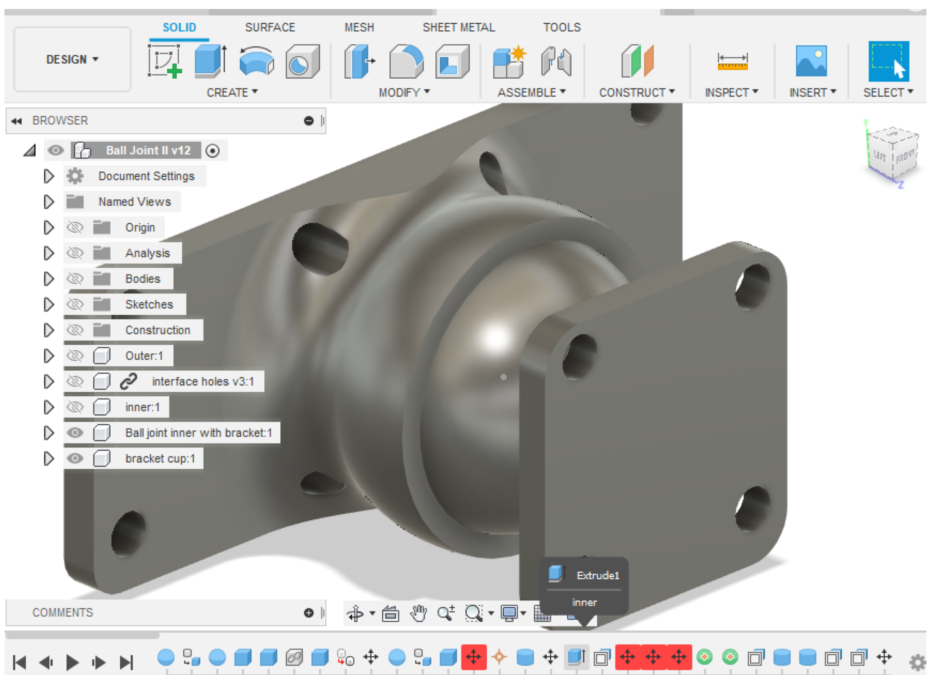



Figure 1.5: Parametric modelling in Autodesk Fusion 360. At the bottom is a history of features added which sum up to the final shape. This feature-oriented flow is useful to track dimensions and specifications of individual features in the history. This method of modelling allows designers to go back and adjust precise angle of a 'bevel' feature, or adjust inner diameter of a 'hole' feature. This style of modelling useful in engineering and manufacturing, where users need precise measurements and modifications to designs according to constraints and manufacturabilty.

### 1.3.2 Polygonal Modelling

Polygonal modelling provides creators with direct control over points connected to form *polygons*, further connected into meshes (Fig. 1.6). In this type of modelling, the fundamental data stored are positions of vertices, and the edges or faces that connect them. It is common to additionally store surface normal vectors at each vertex or at each face. This type of modelling is particularly useful for objects which already have planar qualities, like human-made constructions. This type of modelling is used in most applications of 3D computer renders including film, animation, real-time simulations, and video games for its level of fine control and low computation cost. Several programs commonly used for these applications feature both a polygonal modelling mode as well as a digital sculpting mode [10], [11]. Creators of polygonal models must keep in mind the exact connectivity of the points, and avoid creating invalid or inefficient topologies. This type of modelling has no good analog outside of computers and mathematics. It is not an imitation of life, but a direct reflection of the needs of the computer.

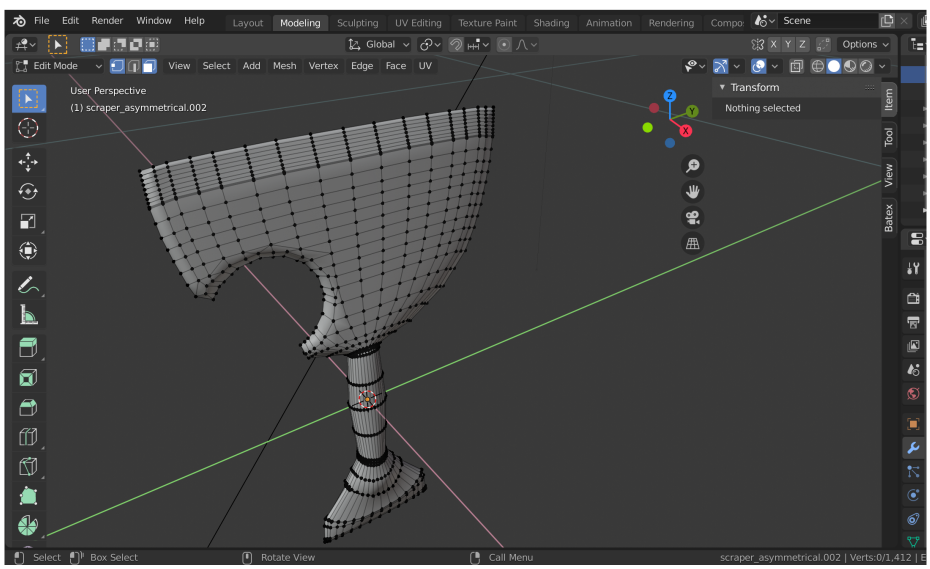



Figure 1.6: Polygonal modelling in Blender 2.8, where users create and modify points, faces, and edges. This representation gives users precise control over the exact topology, and lets authors selectively concentrate detail in areas which need it to visually present well to an audience. Users may move individual vertices in the mesh.

### 1.3.3 Sketch-Based Modelling

Since it is common to design on a 2D plane using computer screens, paper, and tablets, sketch-based modelling leverages a drawing-related analogy. These methods interpret strokes on a 2D-plane into 3D surfaces or volumes, which can see examples of parametric [12] or polygonal data representations [13]. Since the input given is 2D and contains no depth, the computer must infer the user's intent to some degree, sacrificing some intentionality. This method can be the primary method, or commonly, a type of operation in a modelling program with other more precise types of shape creation. In some programs, like Gravity Sketch [14], it is also possible to do 3D sketching in VR (Fig. 1.7). Sketch interfaces offer expressiveness and familiarity to users who are already experienced with pen and paper.

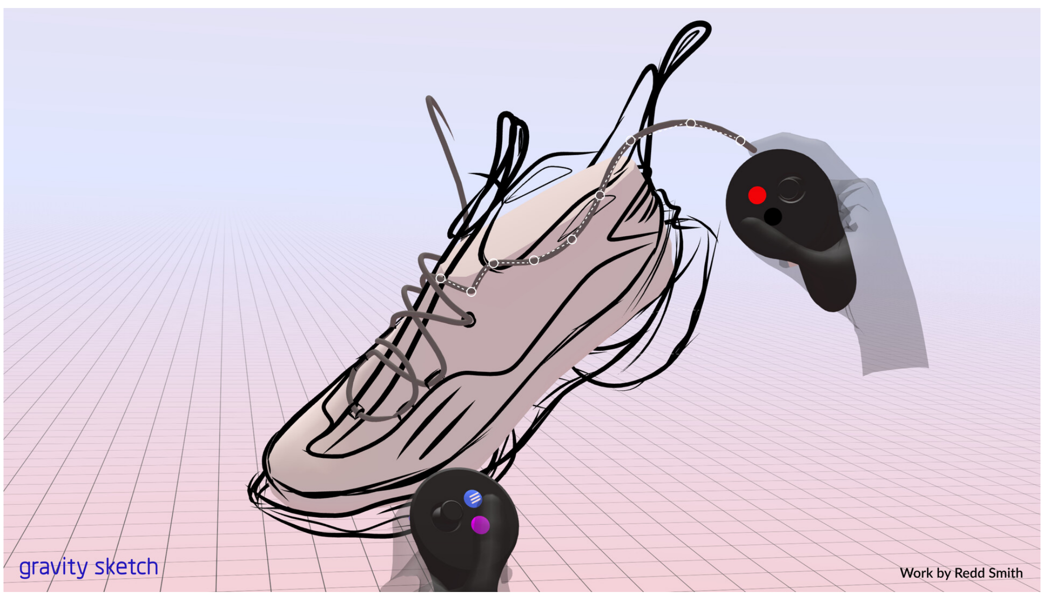



Figure 1.7: Sketching in VR with Gravity Sketch. Each line is a 3D spline produced according to controller motion which may be edited afterward. The familiarity of the line-oriented sketching interface to draftsmen and its freedom of motion allow designers to quickly concept and express ideas, making this method useful in rapid prototyping and product design.

Source: `https://store.steampowered.com/app/551370/Gravity_Sketch`

### 1.3.4 Digital Sculpting


Figure 1.8: 'Sculpting' in Adobe Medium primarily involves applying 3D Boolean Operation CSG stamps to add or remove material. Note that the 'tool' in VR used to sculpt, which is attached directly to the hand. This 'clay' tool will continuously generate geometry at the tip of the pencil with a chosen stencil shape.

Digital sculpting is a common channel for 3D creativity and often a companion to polygonal modelling in the same industries. This mode of creation involves one of two modes: 1. Adding and removing volume using Boolean CSG tools to place shapes, and 2. Painting incremental changes in an area projected onto the surface of an object. It is called sculpting when these things may be done without any concern for features or polygons or lines. While able to produce meshes just as polygonal modelling can, sculpting allows users to create shapes in a more natural, human-intuitive way, reducing the need to consider the underlying edge topology of their models as they would in polygonal modelling, while also having direct control in contrast to parametric modelling. Common digital sculpting software such as Maxon Zbrush [15], 3D-Coat [16] and in VR with Adobe Medium [17] (Fig. 1.8) rely on the metaphor of 'virtual clay' in their presentation, though the models in these programs were never designed to actually behave like clay. To represent the 'clay', digital sculpting programs use either *polygonal*, or *voxel-based* data representations. In the polygonal case, users do not interact directly with the mesh, which is instead dynamically updated as they operate to match the expected user intent. In a voxel-based representation, objects are represented by a set of volume elements (voxels) which contain values that define which space is occupied by material and which space is air. Digital sculpting interfaces allow users to perform many different operations on the virtual clay model, each supporting a similar feature set of common digital sculpting 'brushes' such as 'inflate', 'flatten' or 'twist'. However, just as Microsoft Paint's paint bucket is really an operation, these effects used in digital sculpting are distinctly digital, representing disembodied functions without tactile physics. Analog sculpting involves real clay and physical tools which are both affected by gravity, torque, friction, temperature, imperfections in the medium, and other details not simulated in modern digital art programs. As a result of the core difference in medium and interaction, digital sculpting is more similar to other digital methods than it is to physical sculpting.

## 1.4 Interaction Design

The above methods of shape modelling underline paradigms for thinking about and representing shapes, but control hardware arguably has the largest effect on interaction. The widespread use of keyboard and mouse makes the system a common choice. The tactility, positional control and pressure sensitivity of a pen-tablet system make it a simple step from the mouse as an input device (Fig. 1.9).

Most of the applications described in Section 1.3 use common tried-and-true Window-Icon-Menu-Pointer (WIMP) GUI [18], [19] designs on flat screens with neatly organized boxes of options and effects, which are commonly used with computer mice and pen tablets. Multi-touch enabled tablet displays can allow comfortable and familiar manipulation on a 2D plane for simple tasks [20].

Camera-based tracking can allow users to use hand, mouth or eye motion to interact,

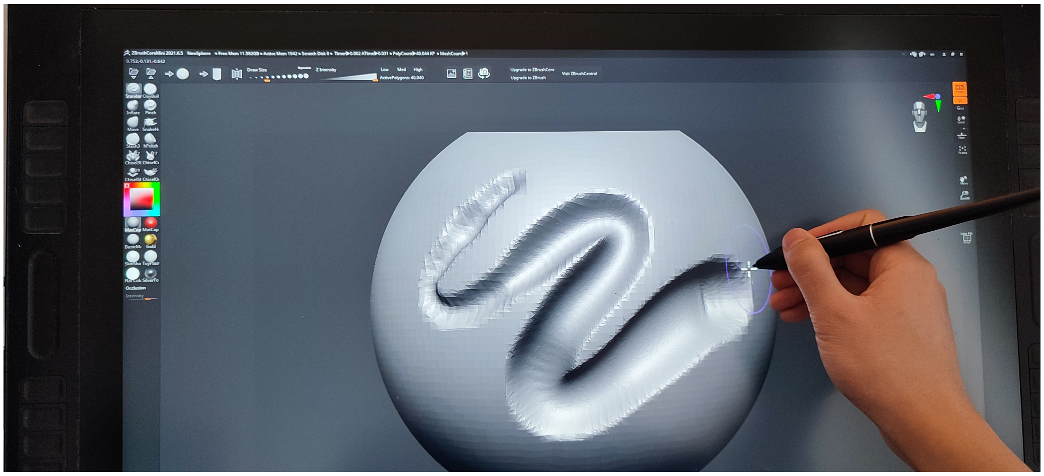
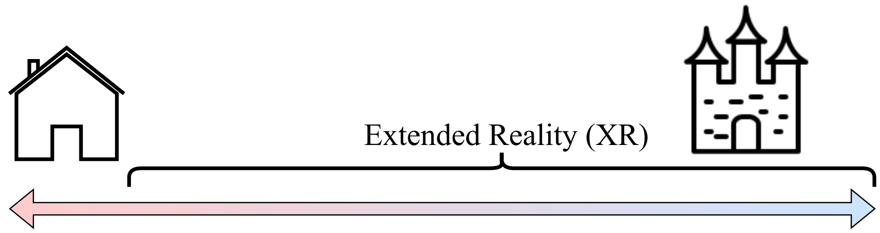


Figure 1.9: 2D pen-tablet interaction with Zbrush, a Digital Sculpting style program. This type of interaction projects the 2D pen position onto the 3D object to determine the position to apply an effect, often using pen pressure sensitivity to control one parameter of the effect, like the depth of a 'cut' operation.

without having to wear any sensors or set up specialized hardware. Haptic force feedback devices allow a program to exert forces on the user based on a simulation of their interaction with a virtual object. We can see them applied for medical imaging, 3D CAD design [21], and alongside physics models of clay for virtual clay sculpting [22]. As an example of new interface research, Sheng et al. [23] experiment with a deformable physical controller– a spongy material acts as a 'proxy' for a digital clay model to allow users to deform it with their fingers. Motion-sensing cameras track the proxy deformation, and the motion of the user's fingers relative to it. Gestures and buttons map to selection and modifying operations in the program, whereas standard modelling programs would contain these within menus and submenus of operators. Though, as much as hardware development can spur our imaginations, it is important that we explore the interaction design within available hardware. Interactive software should take full advantage of the hardware's capabilities and human tendencies. The latter is generally more difficult than the former, leading to the need to study human-computer interaction for each hardware system and problem. As a promising interface for digital art, this research is squarely based on existing VR control systems with a Head-Mounted Display (HMD) and motion controllers in hand.

### 1.4.1 Virtual Reality




| | **Reality** | **Augmented Reality** | **Mixed Reality** | **Virtual Reality** |
|---|---|---|---|---|
| It is... | Our unmodified physical world | Virtual objects placed in an otherwise real world | Virtual and real world are equally present | The real world is entirely replaced by the virtual world |
| You see... | Your backyard | Your backyard, with holographic gnomes projected onto it | A magical garden behind your house filled with projections of mystical flora | A fictional castle keep in a faraway land |

Figure 1.10: In the influential taxonomy by Milgram and Kishino [24], XR technologies may be mapped on a continuum from Augmented Reality, which places virtual objects in the real world, to Virtual Reality, where the real world is entirely replaced by a virtual one.

The advent of Extended Reality (XR) hardware introduced entirely new ways of interacting with computers, expanding possibilities for even more human-intuitive spatial interfaces [24]. "XR" refers to the broad spectrum of alternative digitally-enabled Realities we create with various technologies (Fig. 1.10). Relevant modern XR technologies include mobile phone-based Augmented Reality (AR) SDKs like Google ARCore and Vuforia, Mixed Reality (MR) goggles such as Microsoft Hololens, and head-mounted VR systems such as Index, Rift, and Quest. Many XR interfaces feature 3D stereoscopy and motion-controlled interactions. The advantages of VR systems over other XR alternatives are chiefly the immersion and user acceptance of the new reality. VR substitutes the real world for a virtual one, allowing us to create entirely new worlds with their own laws of physics. Historically, artists learned to create the illusion of 3D objects and spaces on the surface of a 2D plane. As 3D computer manufacturing and graphics came to maturity, they offered new ways for artists to create 3D objects and spaces using 2D computer screens. Now, Virtual Reality allows artists to create in 3D while physically immersed inside their work in 3D. Digital artists do not have to watch through a 16-by-9 porthole on their desk–they can be *present and alive* in it. Architecture, installation art, sculpture, film pre-visualization, and Virtual Reality experiences gain new power when creators can feel the sense of scale and immersion which is to be experienced by their audience. Applications include sketching/painting [14], [25], [26], animation [27], [28], 3D design [29], [30] and sculpting [17], [31]. When it comes to creating digital art, VR is the most native XR interface to digital space. Unless the tools or art being made exist in the real world, there's no reason to see the real world. There may be questions to be asked about the usefulness of using VR pass-through cameras, or AR/MR tools to work on digital art while being *inspired* by the real-life scenery the artist stands within, but this is not the focus of this thesis. The focus of this thesis is digital art interactions, and VR's ignorance of the real world allows the user to focus solely on the digital space being created and experienced.

## 1.5 Thesis Contributions

Intuition, play and experimentation are core to the artistic process. In *What Painting Is: How to Think about Oil Painting, Using the Language of Alchemy* [32], James Elkins writes:

> *Chemistry cannot help to define Monet's mixture, since the ingredients have to be adjusted depending on the picture, the passage, the weather, and the oils and colors that happen to be available. Every act of mixing has to start from scratch, resulting in a batch that is infinitesimally different from every other. A painter knows it by intuition—that is, by the memory of successful mixtures, by the look of the painting, by the scratchiness of the canvas's warp and woof, by the make and age of the paints, by the degree of fraying in the brush. It can just barely be taught, and it can never be written down.*

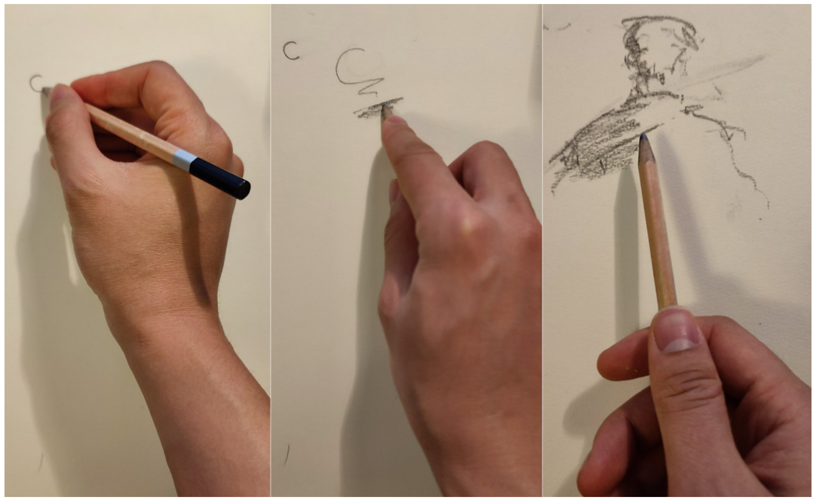


Figure 1.11: An artist may use various grips on a pencil, each with its own profile for range of motion, precision, and power. A firm grip close to the tip (pictured left) may offer bolder lines and high precision. A loose painter's grip far from the tip (pictured right) helps create organic, lively shapes.

Art is experiential by nature. Its processes live in motion and memory. This thesis explores this kind of intuitive mindset in digital tools by introducing an immersive VR environment and a novel class of VR sculpting tools that is more recognizably 'physical' than those in existing work–tools which have physical form, momentum, material, and character. In order to explore this idea to its unique strengths, I needed a starting point. As an artist myself familiar with digital sculpting, I applied my own intuitions to informally determine the following priorities and hypotheses for the new approach:

- Priority 1: User perception of physicality in the interactions between the tools and the medium. Allow users to push and squish clay in a way that feels more like analog sculpting than other methods which do not guarantee conservation of mass.

- Priority 2: Allow users to change their grip of a given tool. In most VR applications, there is only one predefined grip for a tool. However, real artists may swap between grips for different tasks depending on the range of motion and leverage needed (Fig. 1.11). If tools may be gripped in different ways, it will let users pick grips that suit the task better.

- Priority 3: Arbitrary tool topology: No assumptions are made about the shape of the tool. Future iterations may generate a tool from any object imported at any time, or allow users to create tools. If users can use any object to make marks, they will feel greater immersion and freedom in creating. A creative artist may choose to incorporate any object for mark making or deformation, or make their own tools, and an intuitive application should support that.

- Priority 4: Treat each tool as a physical object in a virtual studio, sitting on shelves. If tools may be used at any time in VR simply by picking them up off a table or dropping them it will increase immersion and intuitiveness of tool-switching compared to other, more traditionally digital tool selection methods.

- Priority 5: The new system must have responsive real-time edits and feedback with performance that does not slow down the 80-144 Hz view refresh rates in current commercial VR systems, so as not to make users uncomfortable and to delay cybersickness in the study [33]. The term 'real-time' changes from application to application and the sense of continuity changes based on the temporal resolution of the senses we intend to provide feedback on. In this context, the goal to call this work *real-time* and *interactive* is that it must have changes users make to their working model visually appear at 30 Hz minimum. This is independent of screen refresh rates in VR, changing with the user's head position and orientation at a minimum of 80 Hz. High refresh rate and low latency are key to reducing cybersickness, which also improves presence [34]. Both targets are kept in independent loops to maintain a comfortable refresh rate without requiring the simulation to run at the same minimum rate of 80 Hz.

I believed these factors facilitate more intuitive interaction, immersion, and less frequent tool switching due to the ability to achieve multiple effects using the same tool. These guidelines were used to develop an application which uses a virtual studio, voxel density grid-based workpiece, and physically colliding voxel tools which allow users to pick them up off the table and push them against the workpiece. This was followed up with a study in which various artists tried this tool and other methods to generate feedback on this approach and ideas about what artists need to expand their creativity in VR. The development of this tool also helped test the following hypotheses:

H1: The mass-conserving voxel density model as defined in Section 3 improves user expressiveness compared to Adobe Medium's non-mass-conserving voxel model.

H2: The physical tool model as defined in Section 3.4 which can be picked up, dropped, regripped in different orientations, and placed on shelves with either hand improves user immersion compared to Adobe Medium's non-physical tool model.

Chapter 2 of this thesis enumerates existing methods of paint and clay simulation, real-time fluid simulations, and their applications in creative tools. It discusses Virtual Reality hardware capabilities and programs used for sculpting in VR, giving context to the areas this research spans. Chapter 3 defines the interaction design and simulation methods used to create our virtual sculpting studio environment, including and expanding upon my previous work-in-progress description of the approach [35]. Chapter 4 and 5 outline the design and execution of evaluation for methods of sculpting with artists. Finally, in Chapter 6 overall observations and further questions from the project are laid out to consider moving forward.

# Chapter 2

# Related Work

Prior research in simulation for more natural digital art has explored ways to create with brush bristle simulation, cellular automata, particles, and grid-based fluid dynamics solvers. Current software for 3D shape modelling has developed fast interactions which became industry standard with WIMP interfaces, while VR and optical tracking-related research provide new channels of communication between human and computer, using hand positioning and orientation in 3D gesture-based actions. This chapter reviews the most relevant techniques to contextualize contributions of this thesis.

## 2.1 Water and Stones: Clay as a Fluid

Paint is a substance made of tiny pigment particles suspended in a base medium (Fig. 2.1). Clays in the wild consist of tiny mineral particles and water. Different kinds of paint have different media. Some paints, like acrylic, are water-based and thus can dry to leave a solid structure. Oil paints are made with pigment, binder, and sometimes solvent. They do not quickly dry out, remaining wet underneath the surface for weeks, months, even years. Different kinds of clay used for art have different media. Some clays, like pottery clay, are water-based and thus can dry to leave a solid structure. Clays designed for sculpting can

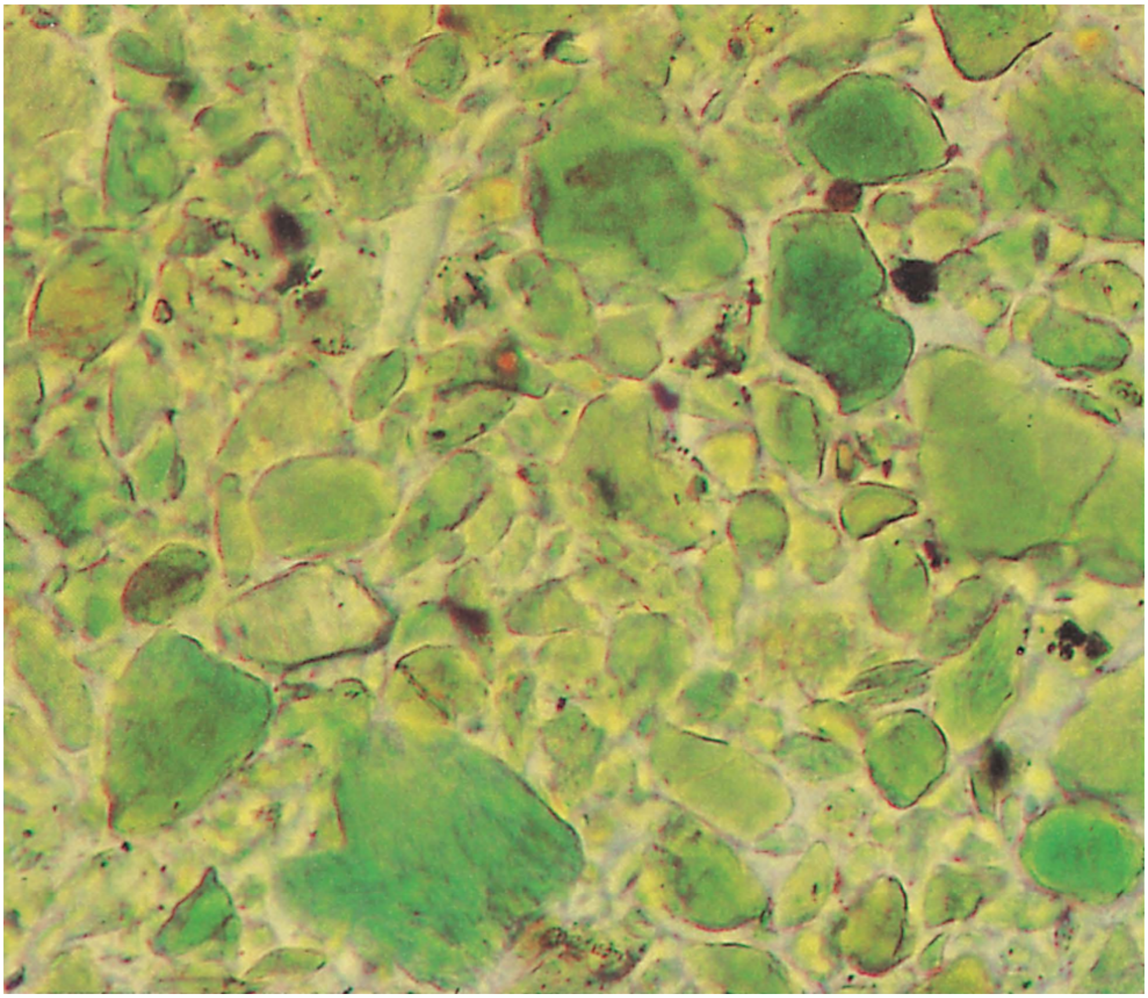


Figure 2.1: A microscope sample of green earth pigment, from page 150 of *Artists' Pigments: A Handbook of Their History and Characteristics, Volume 1*[36]

be made with wax or oil as a base, so that they do not dry out, but instead can melt and become liquid when heated. James Elkins [32] writes of the common identity between paint and clay:

> *Water and Stones. Those are the unpromising ingredients of two very different endeavors. The first is painting, because artists' pigments are made from fluids (these days, usually petroleum products and plant oils) mixed together with powdered stones to give color. All oil paints, watercolors, gouaches, and acrylics are made that way, and so are more solid concoctions including pastels, ink blocks, crayons, and charcoal. They differ only in the proportions of water and stone—or to put it more accurately, medium and pigment. To make oil paint, for example, it is only necessary to buy powdered rock and mix it with a medium, say linseed oil, so that it can be spread with a brush. Very little more is involved in any pigment, and the same observations apply to other visual arts. Ceramics begins with the careful mixing of tap water and clay, and the wet clay slip is itself a dense mixture of stone and water. Watery mud is the medium of ceramists, just as oily mud is the medium of painters.*

Most digital art tools make the assumption that a painting is two-dimensional while sculpture is three-dimensional, and indeed this is mostly true, but in reality, many styles of painting use thick strokes and build up the surface texture on top of more sculptural, even including alternative media. There are also styles of sculpture that reside primarily on a two-dimensional plane, as can be seen in bas reliefs decorating walls, columns, and archways of our oldest structures. This thesis questions the classifications to consider paint and clay as together as being materials consisting of particles suspended in fluid. With the intention of recreating the sense of a *creative clay-like substance*, Computational Fluid Dynamics (CFD) simulation is explored to drive virtual clay interactions for the purposes of 3D design (more in Section 2.3). Incompressible fluid dynamics equations guarantee conservation of mass and can allow users to apply different effects on the surface of their medium using different motions of their hands. By lowering the viscosity of the fluid, we can see melting effects of wax-based clay, or a watery mix of water-based clay–much more liquid. The less viscous a fluid, the more turbulent it can become, creating chaotic results–swirling, flowing, and marbling. For artistic creation, this kind of *realistic unpredictability* can in fact be desirable. One needs only to see the splattered art of Jackson Pollock or any tie-dye t-shirt for reference on how a process involving natural physics can create a desired effect. While the final clay simulation code in this thesis is not a CFD simulation, the introduction of desirable unpredictability is important to the overall approach and data structure.

## 2.2 Finite Element Method

The Finite Element Method (FEM) is a material simulation technique where the medium is represented as a set of particle elements connected by bonds. This type of model could prove to be accurate for solid clay specifically and should also support plastic deformation. FEM is often used for modelling many different physical phenomena in a non-realtime context for engineering tasks [37], including clay & soil minerals involved in civil engineering, fluid flow, and structural mechanics. FEM has can be used in real-time in a low-detail context for mostly rigid structures [38]. However, there are two major factors limiting the utility of this type of approach for this research: 1. Due to the fact that the model necessarily includes connections between nodes, FEM models struggle with significant changes in topology that would come from fluid-like motions as the connections must be edited in addition to the elements. Certain actions like cutting or shearing will either result in artifacts or force performance overhead as the connectivity of elements is recalculated. Non-FEM methods which eschew the concept of bespoke interconnections allow the entire shape to be edited efficiently without requiring the artist to pay attention to these connections.

## 2.3 Real-Time Fluid Dynamics Simulation

To represent clay as a fluid, we must discuss Computational Fluid Dynamics (CFD). CFD is a field governed by the Navier-Stokes equations [39], a set of partial differential equations which define the motion of a fluid. In these solvers, there are two main types of representations: Eulerian (grid-based), and Lagrangian (particle-based). Grid-based simulations are more useful in the context of real-time art support as they are more easily parallelized than particle-based simulations, and scale well with large numbers of elements for high detail. Where a particle-based simulation must track and simulate each particle, a voxel grid offers the ability to divide and simulate sections, and position data does not need to be stored because the location of each element is encoded by its location in the data structure. In grid-based methods, a hierarchical structure can be added where details are sparse. In particular, this research is concerned with using a simplified fluid dynamics solver for real-time applications. Stam describes a real-time fluid dynamics solver which prioritizes visual appeal and speed over physical accuracy [40], [41]. The algorithms he presents propagates velocity and density field via separate diffusion and advection steps. The Navier-Stokes-based algorithms work in both 2D and 3D, and produce stable results at larger time steps and diffusion parameters where others fail, and are simple to implement. The flow of fluids under this method dissipates faster than real flow under the same conditions. For the purpose of games as Stam presented, or for clay sculpting as in this thesis, the goal is not physical accuracy, but to achieve an intuitively plausible material that feels realistic during interactions.

## 2.4 Digital Paint

Digital painting and raster image manipulation software allow users to edit 2D bitmap images by directly changing the colors. Software may be as simple as the ubiquitous Microsoft Paint, or as complex as the industry giant Adobe Photoshop [42]. Colours are stored in either of 1. A subtractive cyan, magenta, yellow, and key ink pigment model, or 2. An additive red, green, and blue light format. To change colors of pixels, operators are used to project raster shapes onto the canvas that may interpolate or otherwise mix colors. Each operator has a specific function and predictable behaviour. Applications leverage common metaphors for their operators such as the Paint Bucket, Pencil, Brush, or Clone Stamp. These common operators are more limited in final effect.

Applications which aim to emulate traditional methods in 2D include Corel Painter [43], and Verve Painter [44] which include more realistic brushes and some aspects of 2D fluid simulation. The significance of simulation-based methods is their focus on the tools and materials rather than only the final effect. In this way, the number and types of final effects an artist may create are less limited and more emergent—subject to their own creativity thinking about the physical interactions being simulated. Here are a few interesting published examples, and their methods:

Baxter et al. presented a painting application using skeletal mesh-based brushes as well as a force-feedback haptic brush model [45]. Individual paint brush bristles move quickly relative to their scale, which produces computational instability over discrete time steps when used in real-time interactions. To combat this, they describe following Aristotelian physics rather than Newtonian physics—meaning inertia is completely ignored (as opposed to Newtonian physics, where it is conserved). They thus modeled brushes as a series of stiff 'bones' covered by a surface mesh. To give users a sense of touch and force-feedback, they used a *Phantom* haptic device (Fig. 2.2) [46]. This particular device provides rotational and translational input, and outputs linear forces and torques in response according to the simulation. The simulation to produce output force commands is often called 'haptic rendering'. The haptic rendering used a piece-wise linear spring for the brush and simple friction. Since haptic rendering has different simulation needs from the paint model, it is done as an entirely separate simulation, with its own 1000 Hz update loop required for smooth haptic feedback. To interact with the canvas, the intersection area of the brush surface and the canvas is computed. 2D paint can be set to 'dry' by slowly transferring

Figure 2.2: A Phantom Haptic Device offered by 3D Systems Inc., formerly SensAble. Image by 3DSystems

Source: `https://www.3dsystems.com/haptics-devices/3d-systems-phantom-premium` from a wet surface layer to a dry layer underneath. A height field on the dry layer allows paint to be piled up in a sculptural, impasto style.

Baxter, Wendt, and Lin expanded on their haptic painting interface from 2001 with a new system titled IMPaSTo [47]. This system added two new components: paint flow using a grid-based fluid dynamics approach, and accurate colour modelling using pigments instead of RGB colours. This was coupled with Kubelka-Munk-based colour model [48] which approximates reflectance of pigmented materials taking into account pigments, their concentrations, and depth. To create data about each pigment, they measured reflectance of real oil paints and mixes on canvas using a spectra-radiometer. This work was able to produce realistic-looking results at moderate resolutions. Storing paintings with a pigment-based colour model also allows its paintings to be accurately re-lit under different lighting scenarios. However, in terms of fine detail, IMPaSTo still lacked the per-bristle details achievable with real paint brushes.

Chen et al. presented a hybrid painting app which used a combination of grid and particle-based simulation to achieve complex interactions between individual bristles of a brush and the paint [49]. The painting app used unique fluid transfer techniques to move particle-based paint between the bristles of a brush and a grid-based representation on the canvas. This allowed simulation at a sub-pixel level and thus create more interesting colour variations visible in real paint. Several optimizations help achieve real-time render performance. 1: Grid-based paint is simulated only within a small region around the brush, with an even smaller region used for particle-based paint. 2: The systems are designed to run in parallel on the GPU as much as possible. 3: The physics simulation of paint on the brush is computed in a reference frame relative to the brush rather than relative to a static canvas. The motion of paint relative to the brush is then scaled down to work at real-time interactive time steps (16-33ms) without losing stability.

Here we see several approaches to simulating paint, or the tools which manipulate it. The primary constraints of these methods are balancing the speed of computation and fidelity of simulation. Often methods must work carefully to introduce simplifications which enable faster performance while preserving fidelity in the areas of concern around paint flow. What these approaches do not cover is the physical interactions involved to select and manipulate tools, nor do they discuss how real artists react to and apply their tools.

## 2.5 Digital Clay

Digital clay sculpting is a common form of 3D creation, alongside polygonal modelling. The core premise of the 'clay' metaphor is that users do not need to consider the edge topology of their work as they would in other more geometric data structures.

### 2.5.1 Voxel Sculpting

In terms of underlying data structure, the virtual clay can be represented by Volumetric Element (Voxel) data or dynamic mesh surfaces. 'Voxel' is a broad term meaning anything in a grid. The data stored in voxels can be binary (filled/unfilled) or continuous, as in the form of a distance field from an implicit description of an object surface. One of the earliest forms of 3D creation involved Constructive Solid Geometry (CSG) operations, consisting of set operators such as Union, Intersection, and Difference performed with 3D shapes as domains [4]. These operations continue to be used in modelling and sculpting applications today (Fig. 2.3).

The first relevant examples of digital sculpting use voxels. Galyean and Hughes presented the first [50] clay sculpting software, with clay represented as voxels. Arata et al. demonstrate local deformations of virtual clay using cellular automata [51], which operate on voxels to move them based on rules to emulate conservation of mass. Druon, Crosnier, and Brigandat iterate upon the work of Arata et al. to optimize the process for real-time application [52]. Wang et al. [53] prototype real-time carving and cutting solid voxel-based hard materials like wood by using tool volumes, being among the first to also represent tools by voxels. Within the broad category of Voxels there are a wide variety of implementations

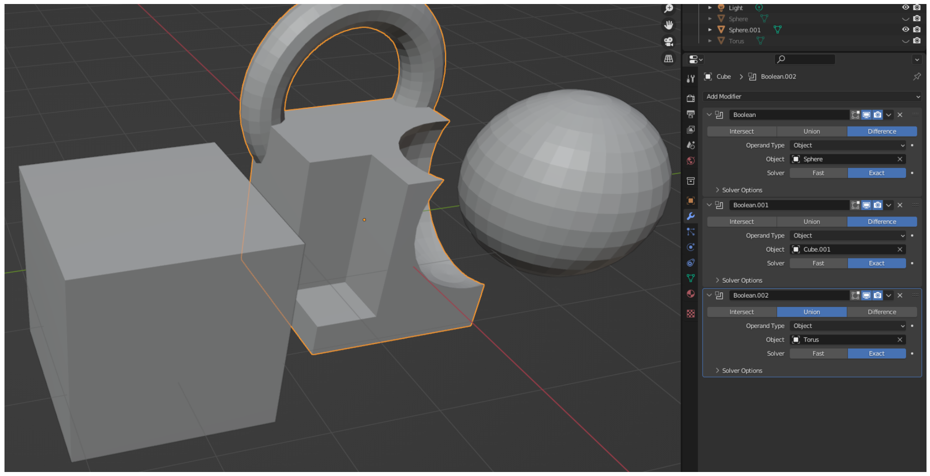



Figure 2.3: CSG operations in the 3D modelling program Blender [10]. The highlighted shape is the union of a cube with torus, minus another cube and a sphere.

and optimizations. For example, Museth [54] presented Dreamworks Animation's "VDB": Voxel-based Dynamic grid based on Binary trees. This work is meant to create an optimized representation of sparse 3D volume data for animation in as high a resolution as possible. Through contiguous memory mapping and masking, VDB implements both random and sequential access, insert, and delete with an average time complexity of O(1). It also supports stencil access to specific parts of the tree in constant time. The hierarchical voxel structure accelerates CSG operations for modifying the model and ray marching for rendering. Museth compares VDB to other state-of-the-art methods to find unique advantages. The sparse representation and thread-safe constant-time functions offer a competitive edge over Dynamic Tubular Grid [55] and Hierarchical Run-Length Encoded [56] methods. The advantages are in memory footprint, editing speed, and rendering. Methods to render volumes like these include variations of Ray Marching and Marching Cubes algorithms [57]. In more specific applications, assumptions may be made to use an alternative data structure to voxels for sculpting, stacked cylinders were used to represent volume-conserving clay, which enables good resolution while avoiding the aliasing issues of voxels, but limits the application to radially symmetric pottery [58], [59].

### 2.5.2 Level sets

Level set methods represent 3D models as an iso-surface from an implicit function [60]. They may be implemented using voxels, if the voxels are used to store a Distance Field to the surface, in which case the voxel grid is the function. A level set may also be implemented by a sequence of functions to define shapes and transformations of the space, e.g. the equation of a sphere $x^2 + y^2 + z^2 = r^2$. In such a case, it will not be limited by the resolution of a voxel grid, but instead is only limited by sampling resolution. Level sets do not have the self-intersection and other topological problems inherent to polygonal models. Being parametric, Museth et. al. [61] describe 3D modelling operations for level set representations of 3D models. To explore this method of modelling, the paper presents operations on level sets that can be used for familiar 3D manipulations. The paper describes how operations are constrained within a local region of influence, or to only add or remove material. Smoothing, embossing, point attract/repel operations are described as a speed function which describes how the surface should move. Though not a unique contribution of this paper, CSG operations implemented as min/max/union/difference of the implicit functions are also presented for completeness. The methods described were demonstrated running in a non-realtime environment, in software limited by a fixed sampling resolution, but they are not limited to these. Modern volume sculpting applications use variations on these operations adapted for real-time use. Noble, Zhang, and McDermott described methods for deforming implicitly defined clay using implicitly defined tools. They conserve mass by 'inflating' the deformed region after an operation until the volume is equivalent [62]. Each time the user applies a tool to the model, it adds to the polynomial defining the shape. Theoretically, this has the advantage of infinite scalability, low storage size, and no loss of detail, but practically it causes the polynomial to grow in terms as the user operates on it, quickly becoming unwieldy to evaluate for real-time operations and rendering.

### 2.5.3 Flat-screen Sculpting

In industry, Professional digital sculpting applications like Autodesk Maya [11], Pixologic Zbrush [15], and 3D-Coat [16] allow users to create freeform solid 3D objects. These applications tend to use the clay metaphor when referring to their sculpting medium, similar to the way digital image editing software uses the paint metaphor. Interactions with the 3D clay can come in the form of projecting the mouse or tablet position into the 3D world to operate along the surface of the object. These applications feature a common set of brushes users of digital sculpting programs will become familiar with–similar to the way digital painting tools have a common set. The common brushes for 3D sculpting include smooth, move, expand, and a suite of CSG operations. All of these brushes have fixed, predictable effects so the user knows what they will do every time they are used, so that they may be more appropriately called 'operations'.

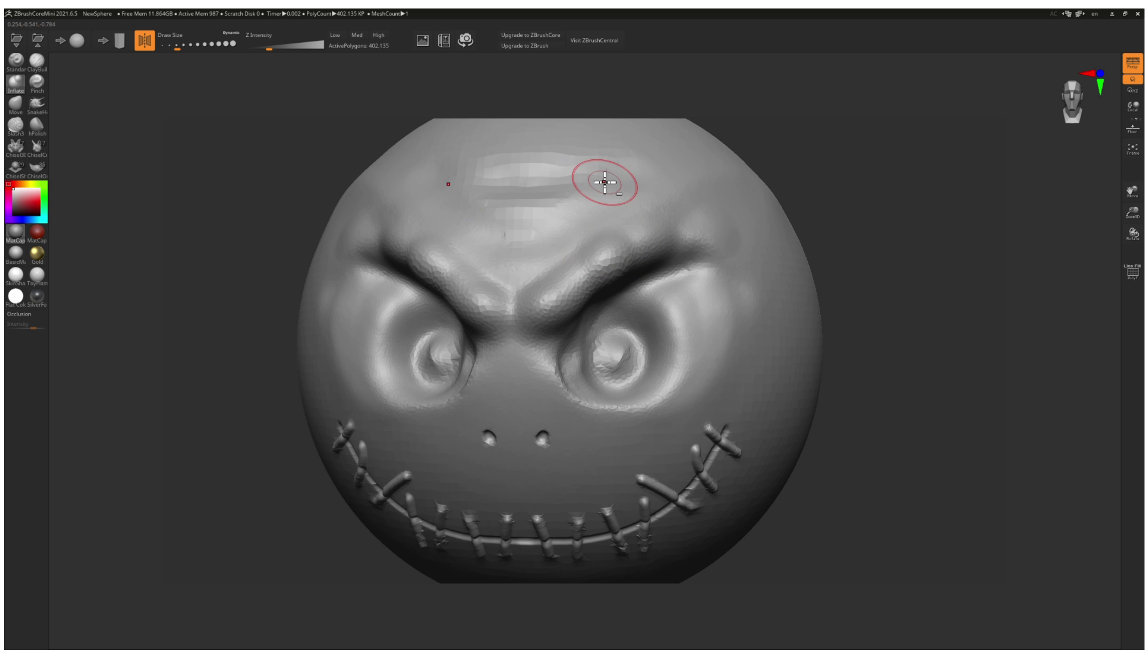


Figure 2.4: Pixologic Zbrush. Note that the toolbar on the side defines brushes by their specific effect on the mesh, not by what type of object it is, since selecting one is really selecting an operation, not a physical tool or brush.

Research on shape modelling operations define methods to deform or generate geometry.

For example, Wang et. al. present a method which applies a Partial Differential Equation (PDE) on a curve patch defined by an eight vertex "frame", in such a way to preserve C0 continuity with neighboring patches [63]. In other words, it applies a simulation style of deformation that can work with models defined by parametric surfaces.

Chen, Zheng, and Wampler present a convenient, content-aware operation for deforming meshes based on solving a system of elastic energy minimization problem [64]. It retains overall shape, is local based on mesh connectivity, and automatically adapts its region of influence.

These above operations do not simulate having a finite amount of material. Angelidis et. al. experimented with a data-agnostic form of volume-conserving operations. They leverage the scale-consistent properties of rotation matrices to deform virtual clay via a series of twisting and pulling motions they call 'swirling sweepers' [65]. One of the main appeals of this method is that such transformations do not rely on a specific data structure.

However, just like the industry applications' brushes, all the above research describe operations, rather than a simulation of any particular type of tool or material. Though the operations developed are useful, there is a significant gap in physically simulated tool 3D sculpting as we see with 2D paints of some work cited in Section 2.4.

## 2.6 Virtual Reality Sculpting

In industry, VR sculpting tools like Adobe Medium [17], MasterpieceVR [31], or SculptVR [66] feature volumetric sculpting. These systems include common operators such as Move, Smooth, and CSG operations. Google Tiltbrush [26], Mozilla A-Painter [25] allow users to 3D-sketch by tracing paths with their hands to create coloured planar ribbons, while GravitySketch [14] does this with parametric curves. In the research space, Eroglu et al. created an application for artists to draw 3D sketches in the air with fluids in an IVE [67]. Users control diffusion, viscosity, brush size, colours, vorticity, and turbulence to create 3D strokes which evolve over time. Users may pause aspects of the sketch and then use tools to pull on parts or blow into a microphone to affect the simulation. To achieve real-time interactive performance, they use a procedural particle-based approach with curl noise in place of simulating turbulent flow. Particles move primarily independently of each other in a time-animated Perlin noise field with an extra internal interaction layer on top. The interactions are approximated by calculating particle densities in a low-resolution grid and moving the particles according to the average density and velocity of neighbouring grid sections. Brush strokes are made by adding particles randomly within the stroke area with velocity. Particles have configurable diffusion lifetimes so that after that time they will stop diffusing until interacted with again. While not physically accurate, this procedural method allows the application to run at high resolution and produces results which look plausible enough to be used for artistic creations.

### 2.6.1 Hardware

Consumer-level VR hardware currently in use includes systems like the Valve Index, Oculus Rift S, Meta Quest, and Meta Quest 2. Each system varies slightly in terms of computing performance, setup, mode of use, and rendering. Input-wise, these systems commonly feature 6 Degrees of Freedom (DoF) tracking of the head and of controllers held in the hands. On each controller are a few buttons and analog axis controls (Fig. 2.5). For output, these systems include high resolution (e.g. $1280 \times 1440$ to $2160 \times 2160$ pixels per eye), high refresh rate (e.g. 80-144 Hz) stereoscopic displays, and simple vibration. Hard limitations we face include render resolution, frame rate, weight of the hardware, precision of tracking, and more, but typically boil down to computational power. Aside from hardware, those involved in Human-Computer-Interaction in industry and in academia are still actively exploring the uses of VR, conventions/modes of use, and interactions, to better accommodate human needs for efficient, intuitive interaction with computers. Improvements to consumer camera technology and optical motion tracking are making gesture-based interactions more viable, though they tend to suffer from imprecision and variance in performance depending on lighting conditions and video quality. Cui and Sourin studied interaction design for 3D modelling with the Leap Motion optical hand tracking device [68]. They use the non-dominant hand to grasp an object, then the dominant hand operates on the grasped object by twisting, rotating, or translating parts of the model. The interactions are designed to maximize precision and avoid cases that produce unwanted effects, such as when one hand occludes the other and interferes with optical tracking. A modelling task presented users with either the hand tracking method or the commercial software Autodesk Maya with a mouse. They found that users of the hand tracking method performed faster, more precisely, and with fewer actions than the Maya testers, but that it was also more uncomfortable and hard to learn.

Figure 2.5: A Meta Quest 2 VR system with controllers, image by Meta Platforms Inc. This particular system uses inside-out tracking, processing depth information of the surrounding stationary environment relative to several cameras on the headset to determine the headset and controllers' position and orientation.

Source: `https://www.roadtovr.com/meta-quest-2-boxes-retail-confusion/`

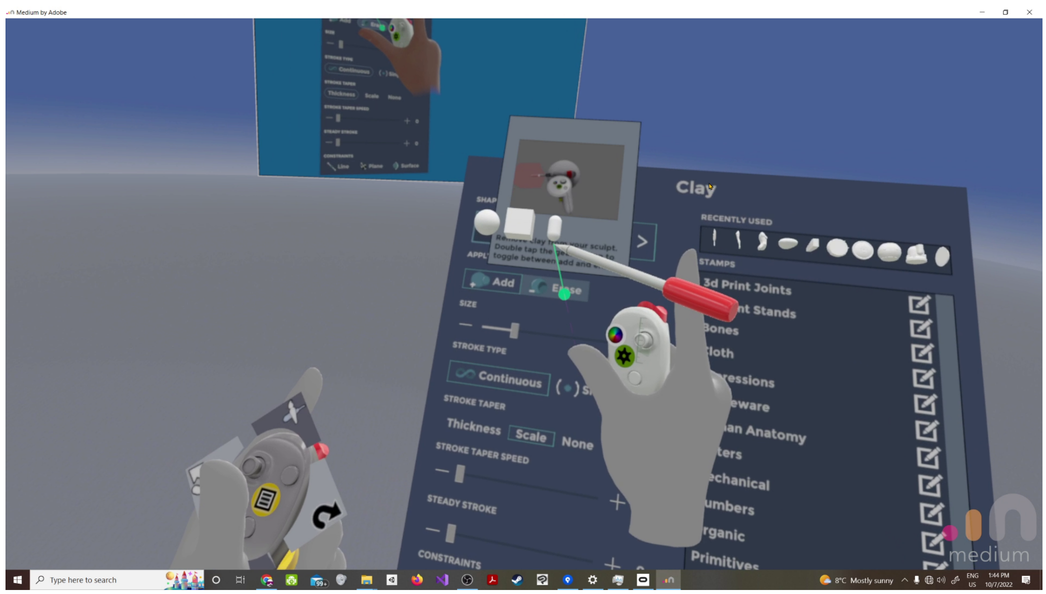



Figure 2.6: Many VR art applications, like Adobe Medium (pictured), use a familiar ‘traditional’ WIMP interfaces for file management, color picking, tool selection.

### 2.6.2 Gaps

Generally, all these interaction models take into account the user's 3D hand position and rotation. However, they lack virtual tools with physical presence. If there is a representation of a tool in VR, they can be seen to follow the user's hands anywhere, and do not collide with surfaces or the virtual clay–instead allowing the user to overlap the tool with the clay to create effects. This ensures the user's real hand always coincides with their virtual hand. The lack of a solid object upon which to rest one's wrist could make it harder to create precise, stable motion. Existing applications with tool selection such as Medium, AnimVR, TiltBrush, etc. also tend to gravitate toward WIMP-style interfaces within VR, treating the controller hands as laser pointers to select icons on a flat plane inside the 3D VR space (Fig. 2.6). These appear to be leftovers of 'traditional' flat-screen interfaces, and may reflect a lack of research into better alternative bespoke interactions for VR.

## 2.7 Where This Work Resides

In this chapter, simulation methods for materials like paint and clay were introduced. Computational Fluid Dynamics is argued to potentially produce desirable behaviour simulating clay for artistic 3D modelling. A common thread lacking in the reviewed research is attention to the user interface design of actually selecting and manipulating tools in natural ways as one does in a studio, opting for WIMP interfaces. Even Virtual Reality approaches tend to ignore the possibility in VR to use interfaces which match a human's natural kinetic and spatial senses. They draw their analogs from computer interfaces, importing concepts of windows, menus, folders, and pointers. This thesis aims to explore a sculpting program which draws its analogs from the real world–to present an environment with a desktop, windows, hands, and tools with presence in the world. One should feel as though one can know an object's possible effects by its shape and physical properties rather than a description of what operation it does. One should not need to 'select' a tool from a menu, but pick it up from the desk. A main limiting factor of such an approach is the speed of real-time calculations. As one of the main constraining factors of other reviewed methods in 2D and 3D, achieving a comfortable update rate for use in VR usually involves making some limiting assumptions about tool use or level of detail. This thesis attempts to minimize programmed-in assumptions about how a tool will be used and instead present it as a solid object which interacts with malleable clay in real-time. In this thesis, real-time performance means rendering visuals to each eye at 80 Hz and updating the data representation of the workpiece where a user sculpts at around 30-60 Hz. Is it possible to create a program that allows users to think in terms of virtual *objects and materials*, as opposed to the underlying *data and operations*? Chapter 3 discusses implementation details on the approach taken.

# Chapter 3

# Approach

Figure 3.1: Virtual Materiality's studio environment. Tool objects sit on shelves, and a ball of voxel clay hovers over the table. The room has a window, lighting, and various ornamental objects to act as inspiraton and a friendly environment. Users may teleport around the studio space or walk with thumbstick controls.

This chapter describes Virtual Materiality, an application intended to explore artistic interactions with virtual clay that more closely simulates properties of real material clay. This description supersedes the previous working paper description of this system [69]. This application specifically aims to differ from existing programs in two main ideas: 1. Tools are treated more as physical objects than as ‘operations’, and 2. The environment (Fig. 3.1) is treated more as a physical studio space than a blank virtual canvas, to better convey the physicality of the tools. Virtual Materiality has no ‘tool selection’ menu with GUI scroll bars, drawers, or drop-downs. Physical tools sit on tables in the virtual studio to pick up and use. Tools and hands may be placed on solid tables, whereas other applications have only empty space with tools for hands.

## 3.1 System Architecture

Virtual Materiality was developed in C++ in the commercial game development tool Unreal Engine, chosen for VR compatibility, performance, and visual fidelity. Leveraging existing features of Unreal Engine 4 [70], Voxel Plugin Pro [71], and the VR Expansion Plugin [72], an immersive VR studio was built which contains several sculpting tools and a virtual clay ‘Workpiece’. For smooth operation, the VR user (input/output), Tools (editing interactions), and Workpiece (data representation) each run on their own parallel update loops (Fig. 3.2).

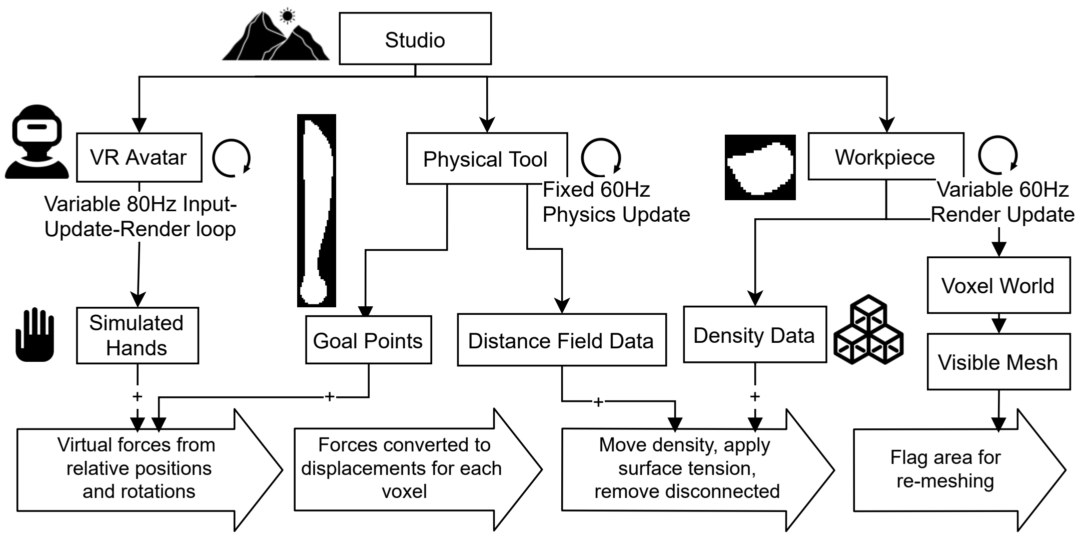



Figure 3.2: The overall structure of the Virtual Materiality system. There are three main components: 1. The Avatar, which contains the physically colliding hands, 2. The Tool, which contains the linear spring force/torque model and the arbitrary tool SDF data used to move clay, and 3. The Workpiece, which represents clay by a 3D density field. The Tool and Workpiece share a logical physics update loop of 60 Hz independent of the VR Avatar update loop, which requires a higher refresh rate to avoid motion sickness. The mesh of the Workpiece is visually updated in another independent re-meshing loop to be rendered at any time by the Avatar's render loop.

## 3.2 Physical Hands Model

The user's avatar supports head and motion controller tracking with a 6 DoF VR headset. It was tested with the Oculus Rift S VR system with a view update rate of 80 Hz. The avatar's hands are bound to the tracked motion controller positions via Unreal Engine's spring-damper constraints model. The avatar's hands have rigid collisions so the user can see them collide with the Workpiece, table, and tools for a sense of Pseudo-Haptic physicality (detailed further in Section 3.6), though the VR system lacks a true force feedback mechanism. In this model, the user can push their real hand holding a motion controller into the clay piece they are working on, while their virtual hand representing their 'proxy' tool collides with the virtual clay and stops at the surface. This creates a displacement vector between the proxy hand's position and the user's real hand. A linear spring is attached between the user's real hand position and their proxy hand position with a resting displacement of 0, meaning it 'wants' the real and virtual hands to be together. The forces produced by this spring increase as the distance between the real and proxy hand increases, providing a way to approximate the forces the user may feel as a result. They are used as input for the interaction between the physical tool and the clay workpiece.

## 3.3 Voxel Density Grid-based Workpiece

The Workpiece is the 'clay-like' sculpting material in this application. It is primarily composed of a Voxel Grid, which supports traditional CSG tools, on top of which was added the new clay simulation. Clay is modelled similarly to a fluid, assuming the 'clay' to be a homogeneous incompressible fluid with high viscosity which will not splash or experience turbulent flow. For user convenience and simulation performance, it was decided not to simulate gravity on the clay workpiece. It will not droop or sag, and disconnected parts do not fall. A voxel-based representation is ideal for three main reasons:

1. Compared to an independent particle-based model, the voxel grid has embedded im-

plied neighbour information. Any voxel has neighbouring voxels which can influence each other, defined efficiently by only their location in an array.

2. Compared to a Finite Element Method model (see Section 2.2), a voxel grid allows the simulation of each clay element to take into account neighbours while still allowing for large changes in the topology of the overall Workpiece.

3. Grid neighbourhoods are more readily parallelizable to achieve real-time update rates.

The Voxel Grid contains integer density values in an octree data structure for efficient access by location. Whenever an edit is needed, relevant voxels are found by finding the intersection of bounding boxes for the Tool and Workpiece. A sampling box is constructed to contain the intersection. The sampling is rectilinear and aligned with the tool grid for easier parallel memory access. This subset of the Voxel Grid data encompassing the area to be edited is converted to a floating point representation where 0 indicates air and 1 represents a saturated clay density (Fig. 3.6). The Voxel Grid reconstructs a mesh using marching cubes [73] which is used for both rendering and rigid collision detection. This meshing algorithm is expensive to run, so it is batched and only runs if the area is flagged as needing updates by one of the editing tools.

## 3.4 Physical Tool Model

The new 'Physical Tool' presented in this paper collides rigidly with the Workpiece and applies displacement based on simulated linear and torque forces. This tool affects the Workpiece in a mass-conserving way, shaping the clay without creating or destroying any of it (Fig. 3.3). This is distinct from other types of 'move' tools in existing sculpting software in that the tool itself is physically simulated ensuring conservation of mass, described in Section 3.4.2. Each tool contains a static 3D mesh for rendering, and a pivot point representing where it is being gripped for torque calculations. The pivot point is determined when picked up, as these tools may be gripped in any position along a spline defining their

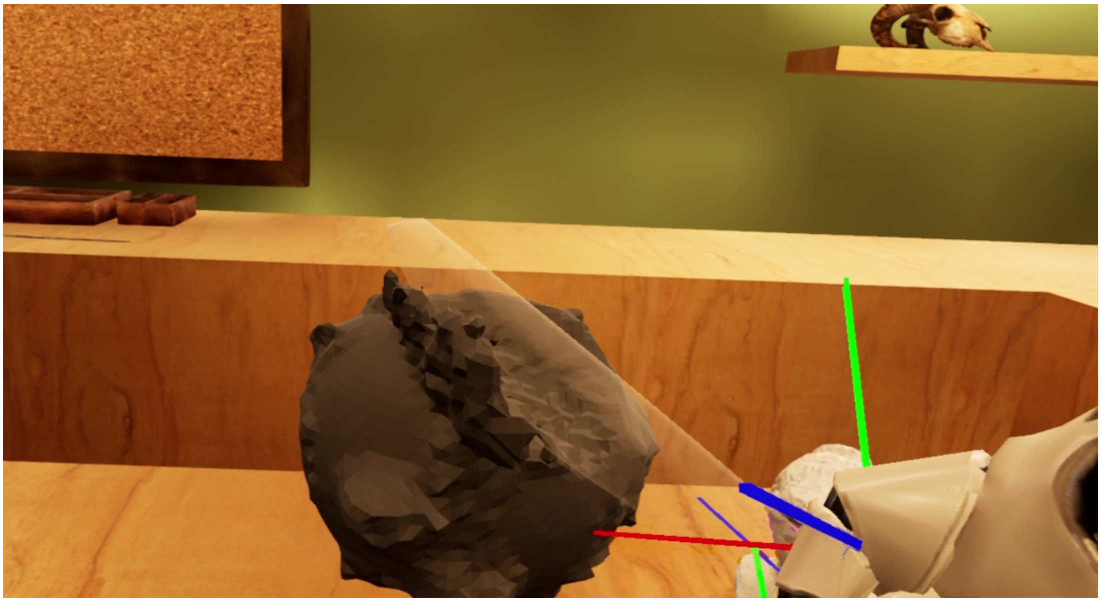


Figure 3.3: Scraping clay using a see-through tool to show the clay moving underneath.

shape, and in any orientation. Each tool is sampled at the same spatial resolution as the Workpiece to create a Signed Distance Field (SDF). A vector field is extracted using the gradient of the SDF and the distances themselves which points each voxel to the nearest point outside the tool. This is used to define, volumetrically, which part of the tool is its outside, needed later when moving clay around. These volumetric representations enable us to apply displacements per-voxel, and allow this system to work with any enclosed shape as a tool (Fig. 3.4).


Figure 3.4: Vector fields visualized in different tools. Each vector field is constructed from the gradient of its SDF, and points outward toward the outside of the tool's surface. These vector fields are used in combination with the to linear and torque forces to determine how the tool will push clay. This model is independent of the geometry of the tool, allowing any shape of 3D object to be converted into a tool.

Tools in this application can be picked up in any orientation and position that overlaps the hand. This contrasts other VR pickup systems which snap the object to one of several developer-specified expected grip slots, which can prevent users from gripping objects in unwanted orientations, but also disallow the user to choose a grip that suits their intention, losing flexibility. Tools update interactions with the Workpiece at 60 Hz and all work is done on the CPU. Each tool which is currently held updates individually in three main steps:

1. Processing Input: The inputs available in VR are positions and, rotations of the HMD and motion controllers. These positions and rotations must be converted into linear force and torque, used in the next step to move clay.

2. Updating Density: recalculate the clay density in each voxel according to forces applied by the tool. Our model includes linear force, torque force, and a collision step to ensure that clay avoids overlapping with the tool.

3. Diffusion: The density update step is mass-conserving, but not volume-conserving. This step attempts to enforce incompressibility of the clay by diffusing high-density areas toward lower density, resulting in intuitive bulging and squishing behaviour.

### 3.4.1 Processing Input

To generate inputs for interaction between the tool and Workpiece, the system uses a model loosely based on the God Object [74] algorithm common in force-feedback haptic rendering systems. The user's avatar's hand can interact with and collide with the virtual world, using the controller as a goal state, receiving forces every physics update to push it toward the goal position and orientation. When the user picks up a Physical Tool, a central pivot point is picked which is closest to the virtual hand's palm position, then three more 'torque points' are constructed in orthogonal directions, for each of three axes. When the user presses a tool against the Workpiece in VR, it collides, but the physical controller may go further.

Tools use the difference between tracked positions in the current and goal states to deform the Workpiece over two main steps (Fig. 3.5). First, linear Force is computed by combining

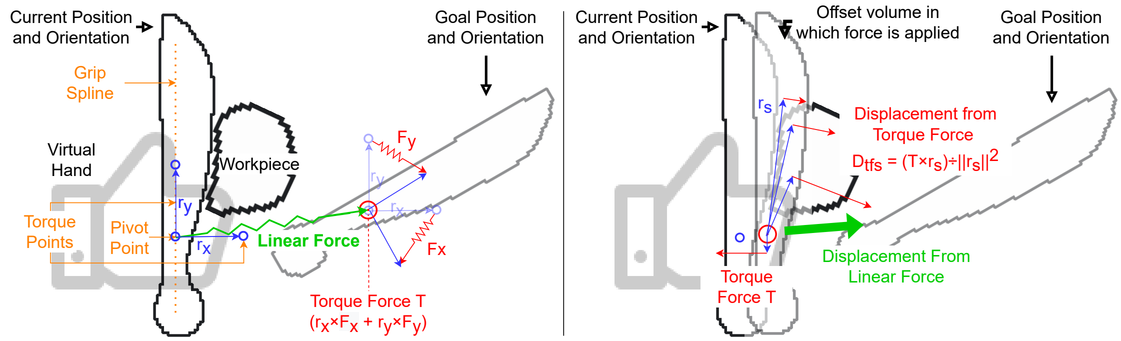



Figure 3.5: Left (input): springs between the goal positions and current positions of the tool pivot and torque points produce linear and torque forces. Right (output): Linear Force and force from torque are applied together as displacements to clay.

the direction to the goal and a magnitude based on the distance between the points. This is similar to the spring equation $F = -kd$, except that an arbitrary curve is a more flexibly tunable model than a spring. Second, torque vectors are computed for each point using a linear spring at each of the torque points between its rotated goal position and the current position relative to the center pivot. The total torque is the sum of the cross products of each of the current local positions and these spring forces. For each voxel of the tool, a lever arm is implied by its position relative to the pivot point, which is used to apply torque. A limitation of this technique is that if the difference in orientations of the current and goal states are greater than 180 degrees, the torque forces applied will flip and begin to decrease in magnitude as the rotation approaches 360 degrees, however, in practice, this condition is extremely difficult to recreate. An issue that is common is that the user's hands or tracking to shake, cause small displacements between the goal and current positions, or for the rigid collision response to create jittery results while pressing the tool against a surface. These create noise in the forces where they were not intended. To reduce errors, the system uses a running mean of computed linear and torque forces over the past four updates. In addition, the force curves used include a minimum distance. These smoothed and thresholded forces are provided as inputs to the next stage: updating the voxel densities.

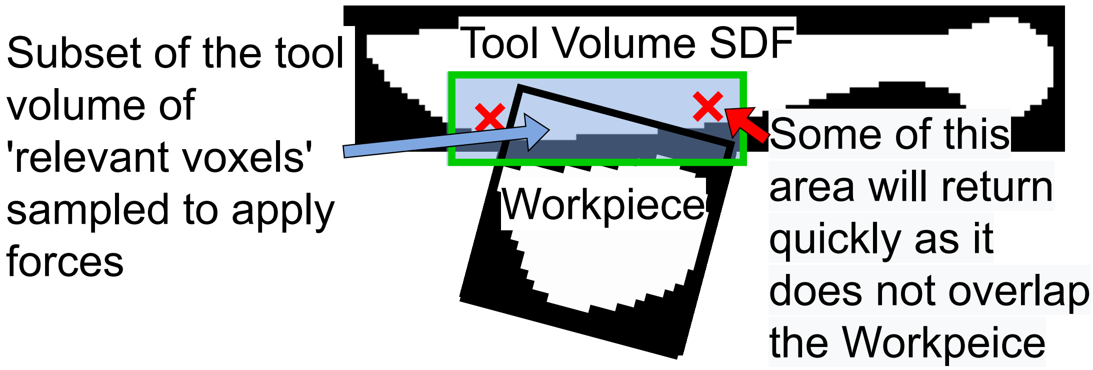



Figure 3.6: The system iterates through relevant voxels in the tool's frame of reference and performs calculations in tool-space (coordinates relative to the tool).

### 3.4.2 Updating Density

The next step in the tool update pushes clay density around in a mass-conserving way. This is achieved quite simply by a 'pick-and-place' method. First, the area of the tool which overlaps the Workpiece is computed. (Fig. 3.6).

For each voxel in that area, linear force, torque force, and prior computed vector field data from the tool are converted to displacement vectors by which to move the voxel density. The density value at the voxel source is subtracted, then looking ahead to the voxel at the displaced destination position, the same density value is added to ensure no mass is added or removed. Each frame of an interaction, five steps occur in sequence in the following order:

#### 1. Linear Force

A linear force is computed from the difference in current and goal positions (as in Fig. 3.5). It is then scaled and added at each voxel to produce a displacement field.

$$\overrightarrow{\text{DLinearForce}_s} = \text{LFScale} * \overrightarrow{\text{LinearForce}} \tag{3.1}$$

Variables associated with a source voxel are noted with the subscript $s$ and destination voxels are noted with $d$. Variables without a subscript are uniform for all voxels.

### 2. Torque Force

Next, a second linear force is computed by the cross product between the total torque vector $T$ and the lever arm between the pivot point and the source voxel position. This linear force is perpendicular to both the total torque and lever arm and approximates how rotating the tool might move mass radially, though not accurate in all cases. This force is also scaled and added at each point to the displacement field.

$$\overrightarrow{\text{DTorqueForce}_s} = \text{TFScale} * \left( T \times \frac{(\overrightarrow{\text{Pos}_s} - \overrightarrow{\text{Pivot}})}{||\vec{\text{Pos}_s} - \overrightarrow{\text{Pivot}}||^2} \right) \tag{3.2}$$

As with other approximation methods described in this paper, these conversions are not truly physically accurate, as they convert force directly to displacement, ignoring momentum. This was done with the intent to save on per-voxel calculations, as the clay-like Workpiece is expected to have high stiffness and viscosity, and nonzero density values in voxels should not vary significantly. For torque especially, this conversion of force to displacement is inaccurate as near a pivot point high forces should correspond to low displacements–the basic property of leverage. This method could turn forces near the user's grip point into unrealistically large displacements of mass. However, this issue is prevented by the fact that a limit is enforced on the maximum distance a voxel may move per operation. The combined displacements are limited to a maximum magnitude $MaxD$. This has the effect of combining them with weights based on their individual scales. It also enables parallelism, as we can simultaneously edit voxels which are $MaxD$ apart from each other without race conditions (Fig. 3.7).

$$\overrightarrow{\text{DTotal}_s} = \left( \overrightarrow{\text{DLinearForce}_s} + \overrightarrow{\text{DTorqueForce}_s} \right) \tag{3.3}$$

$$\overrightarrow{\text{DApplied}_s} = \frac{\overrightarrow{\text{DTotal}_s}}{||\overrightarrow{\text{DTotal}_s}||} * \min\left(||\overrightarrow{\text{DTotal}_s}||, MaxD\right) \tag{3.4}$$

**3. Apply Force Displacement**

This displacement value is used to pick the destination voxel $V_d$ which is to receive the density at the source voxel $V_s$, and the density is updated for the next update. An offset is applied in a direction toward the goal position which biases the range of influence of the tool beyond its current state toward the direction being pushed.

$$\overrightarrow{\text{Dens}_d} = \text{SampleVoxelAt}\left(\overrightarrow{\text{OffsetPos}_s} + \overrightarrow{\text{DApplied}_s}\right) \tag{3.5}$$

$$\overrightarrow{\text{Dens}_s} = \text{SampleVoxelAt}\left(\overrightarrow{\text{OffsetPos}_s}\right) \tag{3.6}$$

$$\overrightarrow{\text{Dens}_{d+1}} = \overrightarrow{\text{Dens}_s} + \overrightarrow{\text{Dens}_d} \tag{3.7}$$

$$\overrightarrow{\text{Dens}_{s+1}} = \overrightarrow{\text{Dens}_s} - \overrightarrow{\text{Dens}_d} \tag{3.8}$$

**4. Apply Vector Field Displacement**

Finally, the displacement step is repeated again, with the tool's vector field data, which points each voxel outward to the nearest point not inside the tool. This forces out density that is still inside the tool, until it reaches the edge, or again reaches $MaxD$. $MaxD$ serves as a limit to improve stability and parallelization. This step is applied as a backup after the force steps 1 and 2 because the force steps follows the user's intended motion, while this step only exists as an additional correction.

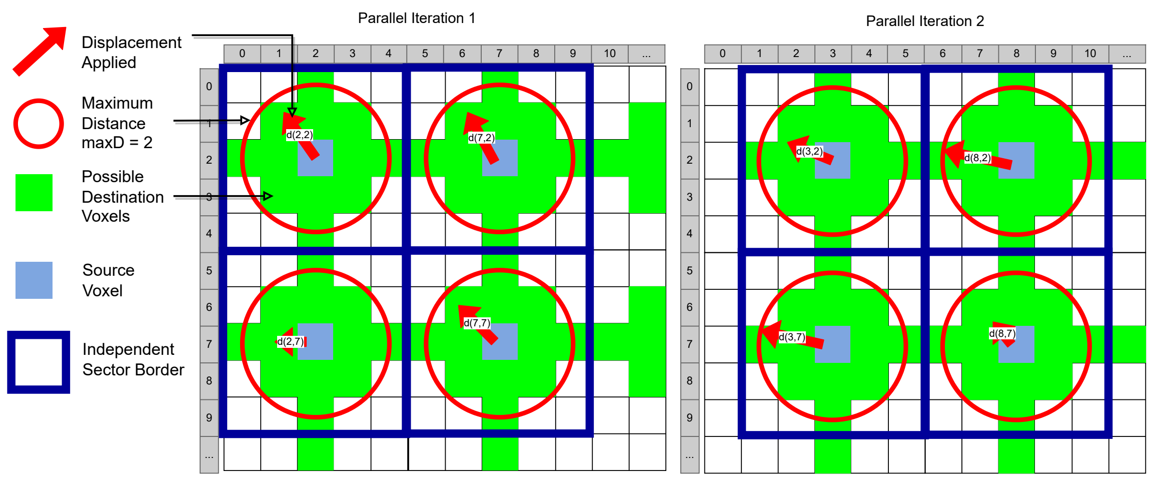



Figure 3.7: To optimize performance, the voxel grid is grouped into sets of sectors of side length $2MaxD$ voxels allow sectors to be computed in parallel without race conditions. After one set of sectors is simulated, another set of sectors can be simulated with different source voxels. Over several iterations, all voxels are updated according to their unique displacement vector. Separating voxels into groups allows different compute threads to work on independent groups.

### 5. Apply Surface Tension

On human hand-sculpting scales, clay materials are relatively dense and incompressible, so this approach chooses to simulate it as such. However, the displacement applied by the previous step will almost certainly result in uneven density throughout the clay. In physics terms, the velocity field is divergent ($\nabla \cdot \vec{v} \neq 0$). After voxel densities have been moved, there are many voxels containing high densities where other voxel densities were pushed into them, particularly at the edge of the tool where the most compression occurs. This causes the Workpiece to lose volume. To reduce this loss of volume, we use an iterative diffusion and 'surface tension' method, as described in the work of Dewaele and Cani [75]. In a series of passes, each voxel is queried for its density value. If it is over the value 1 representing full, then 1/6 of the value in excess is moved to each of its 6 neighbours. This simulates the incompressibility in the clay, causing the Workpiece to bulge as the user moves material around with their tools. Over time, this diffusion step can lead to density slowly bleeding out into its surroundings. Without bonding forces holding the clay together, the diffusion creates either a ballooning expansion effect or a disappearing 'evaporation' effect, depending on the total mass in the system (Fig. 3.8) and the density thresholds used by the re-meshing algorithm to determine which voxels are considered visible. To solve this, surface tension is applied by taking the gradient around each voxel with density below a set threshold. If the gradient is too low i.e. a slow transition from full density clay to empty air, then the voxel's density is moved upward along the gradient toward its higher density neighbours to create a sharper edge.

Figure 3.8: If the diffusion is applied without a surface tension step, the density in the simulation will break up easily, and eventually fill the simulation space with low density values. Tiny droplets can appear when or disappear when the simulation is disturbed, like condensing water vapor.

## 3.5 Boolean Tools

Since the 'Physical Tools' offered in the Virtual Materiality application do not create or remove matter, a set of Boolean CSG 'stamp' tools were also included, as a set of geometric shapes that could be picked up and re-gripped in different orientations just as the other tools may (Fig. 3.9). Each had a defined shape and could be toggled to switch modes between placing or deleting clay with one button. These tools are useful for testing because they represent a match to existing voxel sculpting tools. Adobe Medium uses the same type of operation, albeit without the ability to change grips—the tool is permanently attached to the hand but can have its head change shape.


Figure 3.9: A user in Virtual Materiality adds material with an ellipsoid stamp.

## 3.6 Pseudo-Haptics

The implementation of Virtual Materiality described here contains no haptic, vibrotactile, or audio feedback. It does, however, by its design, feature a Pseudo-Haptic [76] technique. As Mensvoort [77] demonstrates in a study on Pseudo-Haptics on mouse cursor interactions: "*slowing down the speed of the cursor, and the increasing reaction force applied to the input device to compensate for this, induces an illusion of haptic feedback*". Pseudo-Haptic techniques [78] take advantage of resolving conflicts between visual and haptic senses by controlling a new coherent representation of the environment, substituting new laws that govern the visual response to inputs, and by the dominance of the human sense of vision over touch in such visuo-haptic conflicts, creating illusions altering the perception of haptics. Optically Simulated Haptic Feedback (OSHF) are implemented in Virtual Materiality by the spring-force model used to drive movement of clay. Displacement between the current and goal hand positions (Fig. 3.5) is directly proportional to the forces which move virtual clay. The movement of clay density results in a changing mesh, which rigidly resist the simulated current hand position, creating the conflict between visual and haptic senses and the source of displacement used to compute spring forces. The Pseudo-Haptic sensation of stiffness here can be tuned by changing spring constants or $MaxD$ (Section 3.4.2), affecting the relation of displacement between current and goal tool positions to the effects on the clay.


Figure 3.10: The overall flow of physics interactions between the real hand through the physically simulated hand and tool, to the voxel clay model, and back.

## 3.7 Summary

Section 2.7 states that most creative VR applications draw inspiration from WIMP interfaces to select different tools/brushes, failing to fully leverage a human's natural 3D spatial senses to remember where things are. In addition, they make assumptions that each tool/brush will be used in one specific way, meaning they really represent an 'effect'. This thesis challenges these conventions. Chapter 1 described priorities in development: sense of physicality, ability to change grip, arbitrary tool topology, and refresh rate. This chapter described an application, Virtual Materiality, which attempts to balance these in a format suitable to explore its differences from existing sculpting tools in that tools and the studio environment exist as physical objects. The app uses a virtual environment with tables and tools which physically interact with their surroundings. The workpiece is represented by a voxel density grid which is simulated like an incompressible material. There are familiar boolean-type tools and new tools which take any arbitrary shape and interact with the virtual clay in two directions: to push clay and be pushed back by the clay. This new application gives us another unique point of comparison on interaction type to provide us greater perspective in the study, to be described in the following chapters.

# Chapter 4

# Study Design

This chapter details a pilot study to explore artists' experiences sculpting and answer questions about the utility of the virtual space, avatar, tools, voxel density grid-based material and interaction systems which were described in Chapter 3. To generate meaningful insights about approaches to digital creativity support in VR, more artists need to be involved. The Design of Everyday Things [79] describes Human-Centered Design (HCD) as *"an approach that puts human needs, capabilities, and behavior first."* Following this methodology grounds development in real human problems. The study consisted of two main parts. Part A: individual think-aloud trials of three different sculpting methods, each trial followed by a questionnaire and note-taking. This provides the artists with a common basis of comparison and some common language and experiences among them for a follow-up part B: focus group discussion. Overall, the research process from question to conclusion is summarized in Fig. 4.1. The study was conducted in October 2022, during the worldwide COVID-19 outbreak, which affected its deployability and required special ethical care.

| Research Component | | | Description | Results | Materials |
|---|---|---|---|---|---|
| Hypothesis | | | | | |
| Recruitment | | Advertising | Ads distributed on online Greater Toronto Area arts community hubs on Facebook & Discord, Visited OCADU campus, pottery studios, distributed physical posters, emailed digital copies. Poster an emails contain links to sign-up sheet | Gathered diverse artistic minds with multiple levels of experience for whom 3D sculpting programs are relevant to offer their experiences in focus group. 14 Volunteers answered the demographics questionnaire | Demographics & Consent Questionnaire |
| | | Participant Selection | Participant selection criteria are: COVID-19 vaccination, signed consent and acknowledgement of risks, Experience with visual arts, and required to wear masks to appointment | 8 Selected Participants of varying artistic backgrounds. All identified as at least "intermediate" skill in Visual arts, 75% had advanced art education. | Demographic results |
| Gathering data | | Individual Trial Scheduling | Each participant scheduled a separate appointment, to be seen one at a time | All 8 invited attended. Some participants came in pairs and needed to be split up to do trials one at a time | Volunteer Selection/Rejection message |
| | | Brief | All participants who attend individual trial received the $50 gift card participation reward upon arrival | | Individual Trial Script |
| | Trials & Questionnaires | Trial 1 | Methods trialed in different orders selected from a Latin Rectangle | Video recording of in-headset view, audio recording from headset mic, 12 CSI rating 10-level likert scale answers, 3 open-answer | Toronto Studio location, Trial running computer, Polymer clay, Oculus Rift S, Post-Trial CSI Questionnaire |
| | | Questionnaire 1 | | | |
| | | Trial 2 | | | |
| | | Questionnaire 2 | | | |
| | | Trial 3 | | | |
| | | Questionnaire 3 | | | |
| | | Debrief | Surfaces and equipment cleaned with disinfectant wipes to reduce COVID-19 risk | | |
| | Focus Group | Focus Group Scheduling | All participants receive an invite to the online focus group availability form | | |
| | | Focus Group | 2 hour remote video conference | 4 participants attended the focus group meeting | Focus Group Script |
| Analysis | Qualitative Analysis | Theme breakdowns | Common themes from think-aloud statements from trials, observations, open answers from trial questionnaires were compiled, counted frequency of each theme's appearance | | Summary of common themes |
| | Quantitative Analysis | Analysis process scripting | A Python script was written to process quantitative CSI data | Python script for quantitative analysis process | |
| | | Distribution | Calculate descriptive statistics to determine shape of data and viability of different analysis methods. Gathered information on variance, mean, standard deviation, sphericity with Mauchly's Test of Sphericity (a=0.05), normality with Shapiro-Wilk test of Normality (a=0.05). | | |
| | | Correlation of Sculpting Method and CSI Factor scores | One-sided T-test in each direction between each Sculptng Method for each CSI Factor sub-score (average of 2 questions for each factor) | All significant results regarded that Adobe Medium had greater mean scores than Virtual Materiality on | |
| | | Correlation of Sculpting Method and overall CSI score | One-sided T-test in each direction between each Sculpting Method's overall CSI Score | | |
| Conclusion | | | | | |

Figure 4.1: Condensed summary of the research methodology and results in order top to bottom chronologically with horizontal columns describing stages in multiple levels of detail.

## 4.1 Objective

This research aims to obtain insights about future directions for methods of interaction for digital sculpting, particularly in VR. This is a pilot study, aimed at understanding and exploring the constraints and limitations of this medium. There are several questions to explore:

1. How do artists experience sculpting with clay?
2. How do artists experience sculpting in current VR applications?
3. How does the creativity support ability of other methods compare to the 'physical tool' interaction methods presented in the Virtual Materiality prototype?
4. What are the specific needs of sculptors which are, and are not, being met by current digital sculpting methods?
5. Where should future research into digital sculpting interactions focus its efforts?

In addition, relating to the specific simulation techniques contributed by Virtual Materiality, the following hypotheses are tested by a combination of statistical and qualitative analysis:

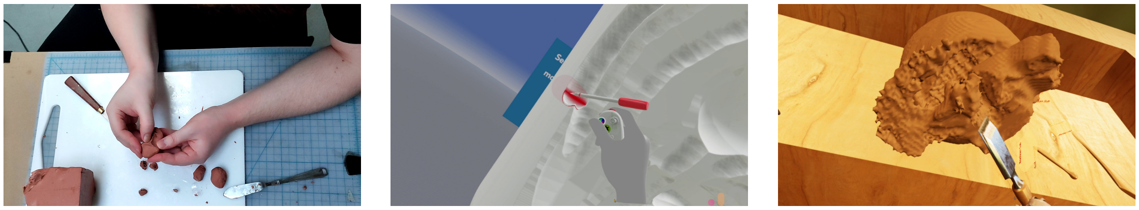
- $H1_1$: The mass-conserving voxel density model as defined in Section 3 improves user Expressiveness and Immersion.
- $H2_1$: The physical tool model as defined in Section 3.4 which can be picked up, dropped, regripped in different orientations, and placed on shelves with either hand improves user Immersion.

## 4.2 Recruitment

In this study, the breadth and depth of skills in the chosen subject matter experts were deemed more important than the number of participants. As an explorative study, it was important to cast a wide net to allow the opportunity to discover new leads outside the expected search area. So, even though the specific subject matter is VR clay sculpting, it was important to gather a broad range of representatives, with the common ground being visual arts experience. Advertisements were distributed by emails and posters to The Ontario College of Art and Design University (OCADU) campus in all wings related to visual arts and in common areas in and around the campus, and the Art Gallery of Ontario (AGO). Digital ads were posted to online artist communities in Toronto, and emails were sent to pottery studios, and the Gardiner Art Museum to forward to patrons. The ads included a link to a combined demographics and informed consent survey (Appendix B). A $50 gift card reward was given for participation and given at the beginning of the first in-person session, with no obligation for participants to stay to receive compensation so as not to disrupt their voluntary participation. Volunteers were told they were also free to share the study and volunteer form with their peers. The sample is intended to represent likely users of VR art creation programs for various purposes e.g. sculpture, previsualization, mixed-media art.

## 4.3 Trials

Participants met individually for one-hour sessions. During this time, participants completed three individual think-aloud trials of three different sculpting methods (Fig. 4.2. Each session lasted 15-20 minutes including basic instruction on using the system, followed by questionnaires (Appendix E). Trial order within subjects was determined by rotation through a randomized Latin Rectangle of the three methods. In practice, the number of participants was not a multiple of the permutations, so two condition orders necessarily must repeat. The rows to repeat were chosen randomly (Fig. 4.3). A script guided consistency in the process (Appendix D).



(a) Subject uses fingernails to imprint en eye socket of a face in polymer Clay.

(b) Subject plays with cutting into edges with the capsule boolean tool in VR with Adobe Medium.

(c) Subject spreads material in VR with a Physical Tool in Virtual Materiality.

Figure 4.2: Stills of different participants' actions during individual trials.

| Subject | Trial 1 | Trial 2 | Trial 3 |
|---|---|---|---|
| J | A | B | C |
| S | C | A | B |
| R | B | A | C |
| H | C | B | A |
| A | A | C | B |
| Y | B | C | A |
| T | C | A | B |
| K | A | C | B |

Figure 4.3: Within-subject study condition list. A: Polymer Clay, B: Adobe Medium The commercial digital sculpting program in Virtual Reality, C: Virtual Materiality, the prototype VR digital sculpting program presented in this paper.

### 4.3.1 Trial Hardware

The tests were held in a rented studio suite. A computer was set up with an Oculus Rift S VR system with Oculus Touch controllers in a 2 × 2m tracking area. The computer used to run the two VR programs had the following specifications:

- OS: Windows 10 Education
- CPU: Intel i7-8700 @3.2 GHz, 6 Cores
- GPU: NVIDIA GTX 1070, 4 GB VRAM
- RAM: 24 GB @ 1196 MHz

### 4.3.2 Trial Procedure

During each session, participants were encouraged to speak their mind and to take mental notes to write about later. They were told that the purpose of these tests is not to evaluate a best or worst method, but to examine the elements of each which may be beneficial for creativity, and to generate ideas for a focus group discussion. Each participant received a personal handout and pencil to keep and take notes themselves for the focus group session (Appendix C). Lastly, there was space for open discussion sessions to share other thoughts and ideas.

Participants were not given specific tasks with each method or significant training prior to the session. On the first time they used a VR method, participants were given basic instructions on using the VR system. Each participant was shown how to hold the controllers, where each button was, how to don the HMD, and how to stay within the tracked area. When using the physical clay, they were told that kneading and warming the clay with their hands would make it easier to work with and that they may use anything they like in the room to help them if they choose.

As this is a pilot study aimed at discovering artist's perspectives first, careful attention was paid to avoid bringing the hypotheses into the discussion during trials. Participants were not informed about the unique features of Virtual Materiality, and were not told of each tool's purpose in the study. No particular attention was brought to the differences between them as the intent was to find what key differences they find, not the key differences proposed by this thesis. As seen in Appendix D, participants were told they were not supposed to do anything in particular other than try out the sculpting methods and share their thoughts. The decision to do this over a task-oriented design was to:

1. Avoid effects of demand characteristics.
2. Observe the artists' natural habits, needs, and thought processes in reaction to the sculpting methods, not the task.
3. Prevent performance anxiety from inhibiting their comfort exploring.

Participants came with varying prior experience with clay and/or Virtual Reality, but all were visual artists, and they did not need instructions to start creating shapes and generating ideas.

### 4.3.3 COVID-19 Impact & Mitigation of Effects

The COVID-19 pandemic's effects on public health concerns forced adaptations to the study design. The number of participants was limited, all participants were required to be vaccinated and acknowledge increased risk, and appointments were spaced to keep participants from coming into contact with each other with time to clean surfaces after each session. The focus group was held virtually. These measures (also in Appendix 6.3) balance the risks of COVID-19 with the potential benefits of this research to art and human-computer interaction. It is hard to determine the exact effect that the pandemic had on recruiting, as no data were gathered on participant perceptions of these risks or ad response rate.

## 4.4 Focus Group

The focus group was a two-hour virtual session on a separate date after all individual trials were complete. It included a short sharing of experiences in turn by each participant, followed by prompted conversation related to the experience of sculpting. The general format of the session can be found in the script, Appendix F.

## 4.5 Data Collection

Data were collected at four points. First, quantitative demographics were collected by questionnaire. Second, qualitative notes were taken during think-aloud trials of different sculpting methods. Third, during each trial, post-trial questionnaires gathered quantitative and qualitative data with numeric ratings and open-ended questions. Finally, an audio recording and qualitative notes were taken during the focus group. The Post-Trial survey was based on the Creativity Support Index (CSI) [80]. The CSI is itself a format based on the NASA Task Load Index (TLX) [81]. The survey distributed in this research consisted of the following set of quantitative questions on the overall experience, randomized (Fig. 4.4), with the only difference from the CSI being the lack of weighting questions, as these and the final scoring was not deemed as important to analyze the differences between experiences with the three sculpting methods as open-format answers and the focus group. Nuances not captured by the questionnaire are captured in the following open-ended response section, where each participant reflected on their experiences (Fig. 4.5).

| | |
|---|---|
| Collaboration | The system or tool allowed other people to work with me easily. |
| | It was really easy to share ideas and designs with other people inside this system or tool |
| Enjoyment | I would be happy to use this system or tool on a regular basis |
| | I enjoyed using the system or tool. |
| Exploration | It was easy for me to explore many different ideas, options, designs, or outcomes, using this system or tool. |
| | The system or tool was helpful in allowing me to track different ideas, outcomes, or possibilities. |
| Expressiveness | I was able to be very creative while doing the activity inside this system or tool. |
| | The system or tool allowed me to be very expressive. |
| Immersion | My attention was fully tuned to the activity, and I forgot about the system or tool that I was using. |
| | I became so absorbed in the activity that I forgot about the system or tool that I was using. |
| Results Worth Effort | I was satisfied with what I got out of the system or tool. |
| | What I was able to produce was worth the effort I had to exert to produce it. |

Figure 4.4: Post-Trial CSI Questionnaire items. Each was rated on a disagreement/agreement scale from 1-10. Each question belongs to a pair supporting one Factor of creativity

| |
|---|
| Please describe your overall personal experience using this method of sculpting. |
| Specify the physical sensation of working with this method of sculpting. For example, how do your hands physically feel holding the tools or controller? |
| Specify the mental experience of working with this method of sculpting. What were you thinking about? |

Figure 4.5: Post-Trial Questionnaire open-answer questions

## 4.6 Analysis Methodology

To capture the valuable non-numerical ideas and discussion of the artists as subject matter experts, a thematic analysis was performed as pictured in Fig. 4.6. Notes taken based on participants' think-aloud statements during trials, open-answer comments in the questionnaires, and opinions stated during the focus group were compiled together and encoded into common themes. Each theme was counted by how many of the participants it was seen in, and the list was sorted by these instances. To focus on the most critical issues, only themes with five or more (majority among the total of eight) instances/agreements among participants were included. An interpretation was written on what each may imply (Fig. 5.2). To facilitate numerical comparison of the creativity support, statistical analysis was performed on the questionnaire data. Post-Trial CSI Questionnaire scores were compiled together and the distributions of each were analyzed to test for non-normal distributions and violations of sphericity which may necessitate different approaches to analysis. Then, independent-sample one-tailed T-tests were done in each direction to determine if and how the method chosen influences their ratings in terms of six CSI factors and the overall average. Detailed results of the statistical analysis follow in Section 5.4 This concludes a review of the components of the study. Chapter 5 discusses the raw outcomes and trends from the participants' survey responses and comments.

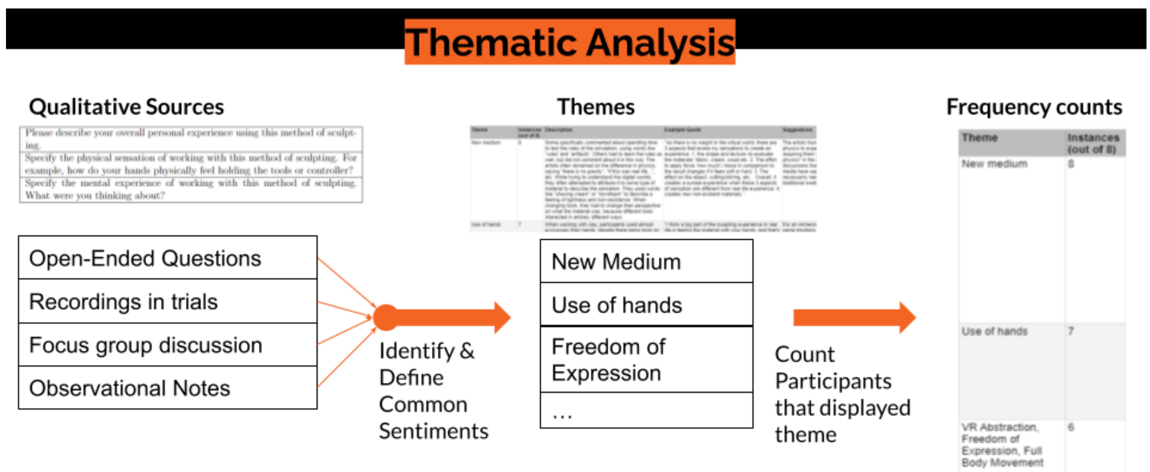



Figure 4.6: The process used for coding and counting themes from feedback, notes, the focus group, and recordings which resulted in the theme summary in Fig. 5.2. This process corresponds to the "Qualitative Analysis" step in Fig. 4.1.

# Chapter 5

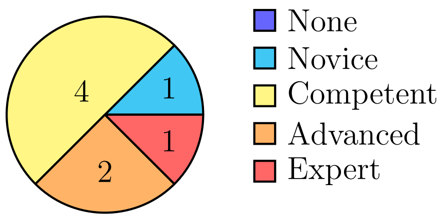
# Study Results

This chapter presents and discuss the raw data, trends and quotes from the study described in Chapter 4. Finally, Chapter 6 relates these findings to the original questions and hypotheses. For a full overview and summary of the study process from recruiting to analysis, refer to Fig. 4.1. The small size of this study permitted each individual involved to be more involved in their interviews and direct observation. During trials, it was clear to see the individual backgrounds of the selected artists informing their opinions and views on the processes. For example, some artists were most comfortable using computers for art, while others prefer to keep their distance from them. In this case, both opinions are relevant because this research aims to help narrow that gap.

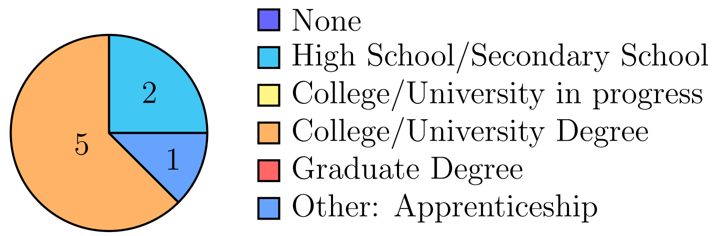
## 5.1 Demographics

The focus group study had a total of eight participants: four male and four female, aged 24-41, with a mean of 29 years. They had various combinations of skills as a ceramicist, pen-and-paper draftsman, videographer, machinist, game user researcher, and musician. Demographics were collected prior to participant selection to be able to choose relevant candidates (full results in Fig. 5.1). Information used included profession(s), skill with computers, level of formal education in the visual arts, experience with analog sculpture, experience with 3D digital sculpting, experience with Virtual Reality, experience with Adobe Medium, gender, and age. Questions regarding levels of experience used the following scale to collect a broad indication of confidence:

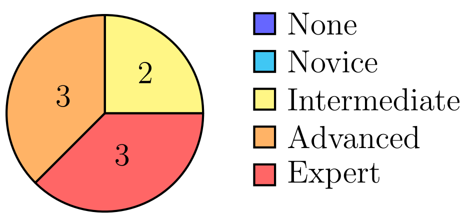
1. None
2. Novice (e.g. less than 10 hours of practice, or a few days)
3. Intermediate (e.g. more than 100 hours of practice, or 1 month)
4. Advanced (e.g. more than 1,000 hours of practice, or 1 year)
5. Expert (e.g. more than 10,000 hours of practice, or 10 years)
6. Do not understand/unable to answer the question
7. Other



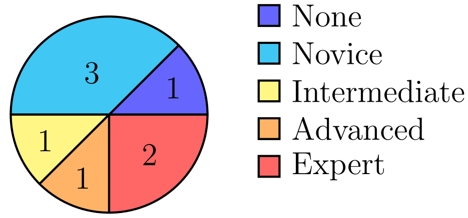

(a) What is your level of skill with computers?



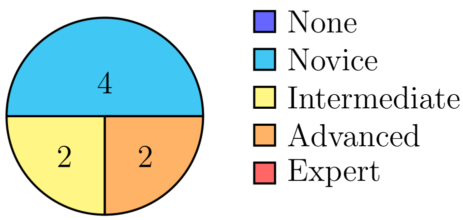

(b) What is your highest level of formal education in the visual arts?



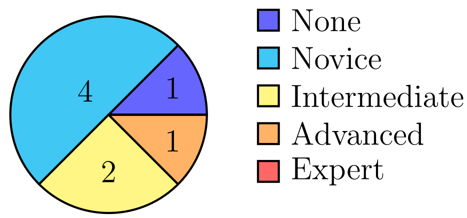

(c) What is your level of experience in the visual arts?



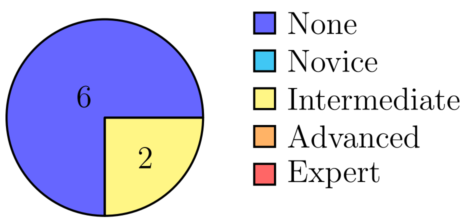

(d) What is your level of experience with analog sculpture of any kind (stone, clay, papercraft, etc.)?



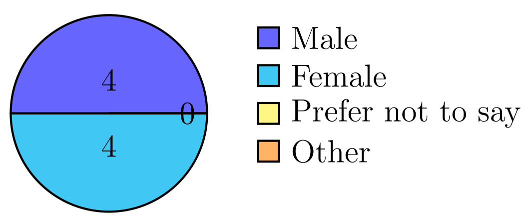

(e) What is your level of experience with 3D digital sculpting programs (e.g. Blender, Cinema4D, Maya, ZBrush)?




(f) What is your level of experience with Virtual Reality?




(g) What is your level of experience with Adobe Medium?




(h) What gender do you identify as?

Figure 5.1: Demographics Results of eight invited participants who attended trial sessions with all three methods of sculpting. Only those with an artistic background were selected. On the whole, users were less experienced with VR and digital sculpting.

## 5.2 Focus Group

After all participants' individual sessions, they joined a two-hour online conference call to discuss findings. Attendance was not mandatory as they had already been provided gift cards on the first session, and participants were allowed to leave the call at any time, so only four attended the full session from start to finish. The group agreed that based on their experiences, VR sculpting tools are best used for prototyping, particularly when prototyping things we expect humans to be immersed in, like architecture, analog installation work, or other VR experiences. When asked what would make the difference for them to consider it in final productions, they suggested the following additional requirements:

- Touch: Capturing texture and resistive forces.
- Detailed use of hands: ability to use thumbs and palms.
- Realization: Add a scanner, so you can use something you made traditionally in a digital context, and a printer, so you can use something you made digitally in a physical context.

In the focus group session, the artists were very keen to point out the importance of the pressure and texture information missing in their digital experiences as limiting factors for them. Users who saw their virtual hands hoped they could touch and feel the clay with their fingers. One mentioned that as a digital creation tool, VR, in comparison to mouse and keyboard, offers less speed and precision for things they know how to do. Others mentioned they really liked the freedom of expression when experimenting. One artist spoke strongly about keeping digital experiences digital, because when the veneer of realistic physics is introduced, it also introduces many other expectations which cannot be met. They argued that they prefer if a digital program remains "unapolagetically digital", and that blurring the lines caused "disconnect" when their experiences is different. This partially aligns with statements from other artists. Others agreed that they did not have 'realistic' experiences so far, though some remained hopeful. In one individual conversation, two participants discussed the viability of VR for physical production, making the case that it is difficult to imagine including it in a workflow that produces real, physical objects. This, combined with other discussions about the strengths of digital being separate from the strengths of the analog, highlights the importance of improving ways for artists to easily transport their ideas between digital and physical boundaries to suit their needs.

## 5.3 Qualitative Analysis of Themes

Think-aloud trials and open answers from the artists in the questionnaire, and focus group discussions lead to interesting comments we can examine. The table in Fig. 5.2 enumerates some themes and interesting ideas generated by the artists' trials, and describes my thoughts on their implications. The two most pervasive themes were that VR was seen as an entirely different medium with its own rules (seen in all eight subjects), and that when given polymer clay, users nearly exclusively used only their hands to feel and mold the clay, despite the availabilty of tools (seen in 7 of 8 subjects). The one subject not to use their hands on the clay had spent the entire session repeatedly dividing the clay in two with a knife, contemplating about its seemingly infinite divisibility into smaller and smaller pieces. Notably, this is a feature not easily replicated in a program. Final conclusions taking into account these themes and the quantitative results and their relevance to the original research questions of this thesis will be discussed in Chapter 6.

| Theme | Instances (out of 8) | Description | Example Quote | Suggestions |
|---|---|---|---|---|
| New medium | 8 | Some specifically commented about spending time to test the rules of the simulation, using words like `rules' and `artifacts'. Others had to learn the rules as well, but did not comment about it in this way. The artists often remarked on the difference in physics, saying "there is no gravity", "if this was real life...", etc. While trying to understand the digital worlds, they often attempted to attribute it to some type of material to describe the sensation. They used words like "shaving cream" or "styrofoam" to describe a feeling of lightness and non-resistance. When changing tools, they had to change their perspective on what the material was, because different tools interacted in entirely different ways. | "As there is no weight in the virtual world, there are 3 aspects that evoke my sensations to create an experience. 1. the shape and texture--to evaluate the materials: fabric, cream, wood etc. 2. The effort to apply force: how much I move in comparison to the result changes if it feels soft or hard. 3. The effect on the object: cutting/stirring, etc... Overall, it creates a surreal experience when these 3 aspects of sensation are different from real life experience. It creates new non-existent materials." | The artists found some aspects of the new laws of physics to expand their possibilities, while also requiring them to learn more about the "new laws of physics" in the program. We find later in the discussions that the participants feel the digital media have separate strengths which do not necessarily need to encroach upon the strengths of traditional media. |
| Use of hands | 7 | When working with clay, participants used almost exclusively their hands, despite there being tools on the table. Particularly actions of squeezing, pinching, cutting, and rolling. VM had hands, which suggested they could use their hands too touch the clay. They could not. AM only had controllers and tools to replace the hands, hence they did not question if they could use them or not. | "I think a big part of the sculpting experience in real life is feeling the material with your hands, and that's something that's missing in VR. It's made me notice things that I wouldn't think too much of when sculpting in real life, like mass or texture." | For an immersive VR clay simulation to follow the same intuitions artists expect of realistic clay, the thumbs, index fingers, and palms must be involved to support squeezing and rolling |
| VR Abstraction, Freedom of Expression, Full Body Movement | 6 | Without any prompts, most sculptures made in Clay were representational, while some were just used for play. When put into VR, artists jumped straight to the abstract. The artists described feeling free and `having fun'. Upon discovering it they tended to prefer to expressing themselves using Boolean Tools, making large sweeping motions to create streaks of clay with their handheld controllers. | "The ability to use the entire body when sculpting made the process feel very kinetic and enjoyable. However, I found that [Adobe Medium and Virtual Materiality] lacked the precision of traditional modeling and sculpting software like Maya or ZBrush." | There may be multiple factors involved in this. The virtual environment, the new physical rules & lack of gravity in the digital context, and the lack of physical obstruction or force feedback in the hands. These factors lead users to feel free and light, and support a different type of expression not necessarily seen as superior or inferior to clay. The expression seems to commonly be about the motion of the whole body, which is possible with VR when there is no physical resitance to motion from the material. The kinetic "free" aspect of motion and creation in VR is one of its special features and enjoyable part of VR artists' expression |
| Boolean Tool's suitability for VR | 6 | In Adobe Medium, the boolean add/remove clay tool is the de-facto primary action of the program. In the trials for Virtual Materiality, artists often gravitated toward the in-app provided boolean tools instead of the `physical' tools once they tried it, regardless of the order they tried the different programs. | "Being able to intersect without physical interaction helps when adding material to a crevice, since in real life, adding material deforms the rest" | Adding and deleting material in a known shape felt the most useful to users in the VR sculpting context. This gravitation may at least partially be affected by its novelty, but such types of tools have been commonplace in programs for a long time. They clearly have advantages with more longevity, as can be seen in the quote here. Boolean addition/subtraction from a set is also one of the most `natural', simple operations to do in a voxel-based sculpting program based on the data structure, and so perform very precisely and fast. |
| Flow State | 6 | When using clay, all except the machinist and game user researcher specifically described their experience as "tuning out", "not thinking", "flow", or in one case showing it by spending the entire session continuously slicing the clay into smaller and smaller pieces. This sort of automatic flow was not nearly as frequently described with either of the digital methods. The digital methods frequently contained phrases like "thinking about" or "trying to". This reflects that the digital experiences . People thought about scale, about tools, about the programs themselves. In both digital and physical cases the participants seemed focused on their material, but the digital programs were more often described with words involving effort. | "Embodied contact was first, that was grounding, I had a choice of engaging more conceptually or with more coscious effort when I wanted to but also I could just let my hands go without thinking about it, and was grateful for the sensory feedback and the force exerted by the density and weight of the object, it is strangely comforting to have something to push against." | This may be simply explained by the fact that for most these programs were new and unfamiliar, while the clay is fairly universally familiar. Even so, it is tempting to think that its simplicity is a natural advantage of the analog. In addition, as long as users recognize that the digital sculpting imitation is artifice, they can more easily question the design of this artifice than they could real laws of nature. So, it is easier to end up thinking about digital tools than it will be to think about physical ones. |
| Sensory Vacuum, Lack of Touch | 5 | When users compared clay to VR, they felt that VR was missing the sense of touch and resistance | "With Adobe, with the lack of touch... it was a… sensory vacuum."<br><br>"Playing with the physical material, squeezing it and rubbing it, these actions itself is a communication with the material, getting to know it, without an object of making an 'art work'. Art lays in this communication of getting to know, and thus connected"<br><br>"...the lack of actual physical medium being there it is hard to guide the tools" | Haptics are an important part of the communication between artists and the material, and to making precise actions possible |

Figure 5.2: Summary of common themes observed in the trials. The "Instances" column indicates in how many of the participants this observation was made, directly in the open-answer questions of a post-trial questionnaire (as in Fig. 4.5), or verbally during or after the trial. Only themes seen in the majority of participants were included. Each is accompanied by an "Example Quote" pulled from written open answers of one or more of the participants. Finally, the "Suggestions" column interprets the theme's implications.

## 5.4 Descriptive Statistics

Eight participants each provided 12 numerical CSI question Likert-scale responses for each of three within-subject trials. In total, there are 36 individual Likert answers per participant. The 12 questions are paired and averaged into 6 Creativity Support Index factors from 1-10. They were grouped by sculpting Method to create histograms of Scores by CSI Factor. For each sculpting method, all individual question responses were averaged to create a Final Score in the range of 1-10 representing overall effectiveness of each method in supporting creativity. In total, there are 48 CSI Factor scores for each sculpting Method (6 from each subject), and 8 Final Scores (1 average of each). Histograms for each are presented in figures 5.3, 5.4, and 5.5.

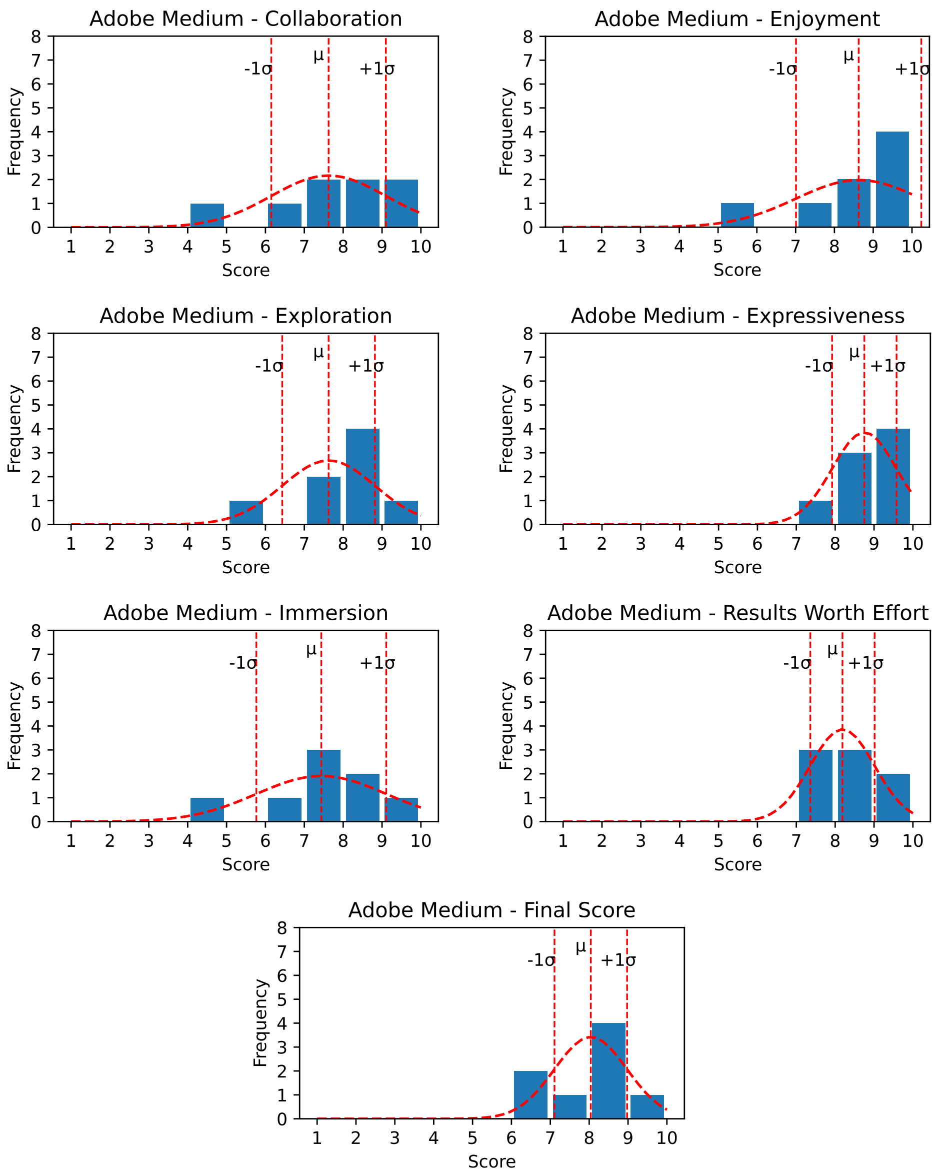



Figure 5.3: Histograms of Adobe Medium CSI Factor scores. Overall, they reflect faily consistent positive prospects as a creative tool. Compared to other tools, Adobe Medium scores had lower standard deviations. Mean, Standard Deviation, and a normal fit are shown in dotted lines.

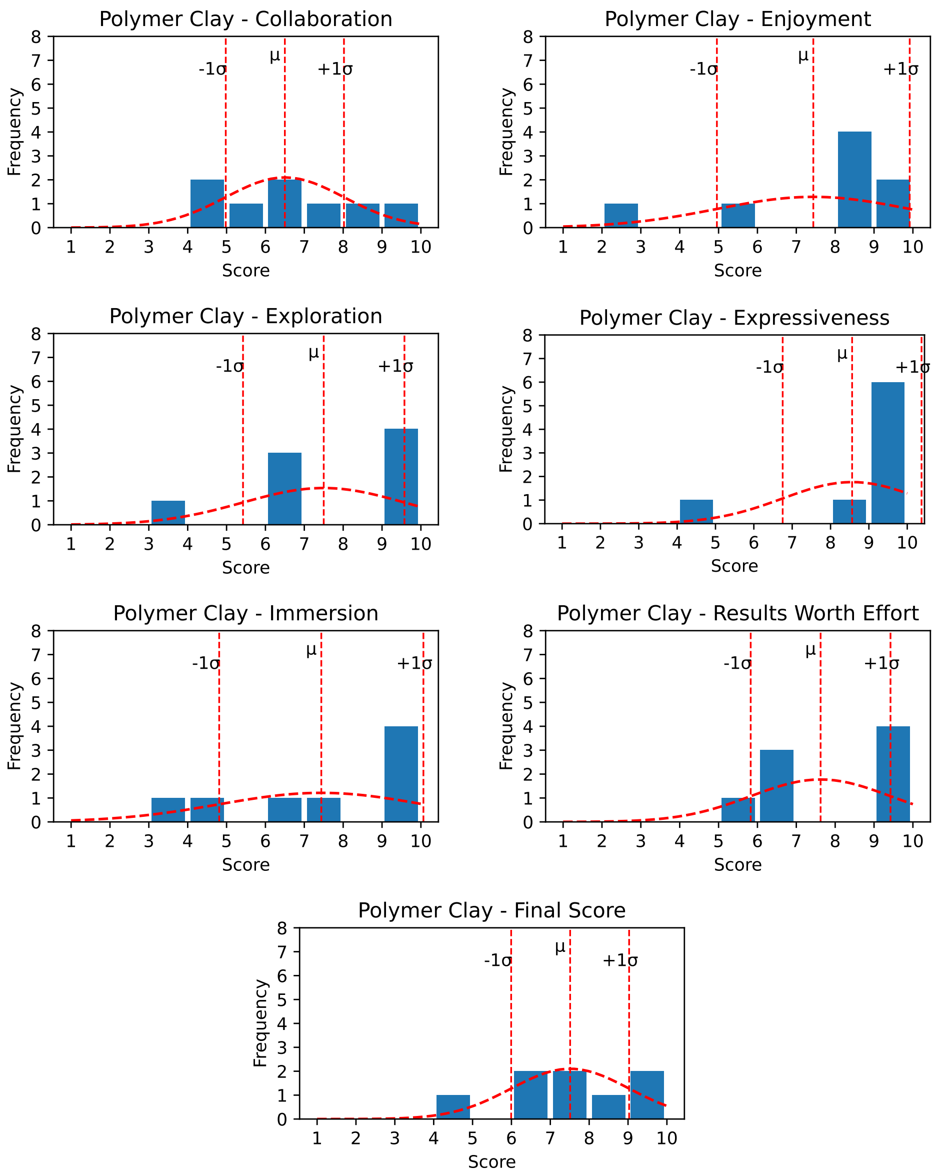



Figure 5.4: Histograms of Polymer Clay CSI Factor scores. Overall, opinions on this method of sculpting were divided between excellent or mediocre. Mean, Standard Deviation, and a normal fit are shown in dotted lines.

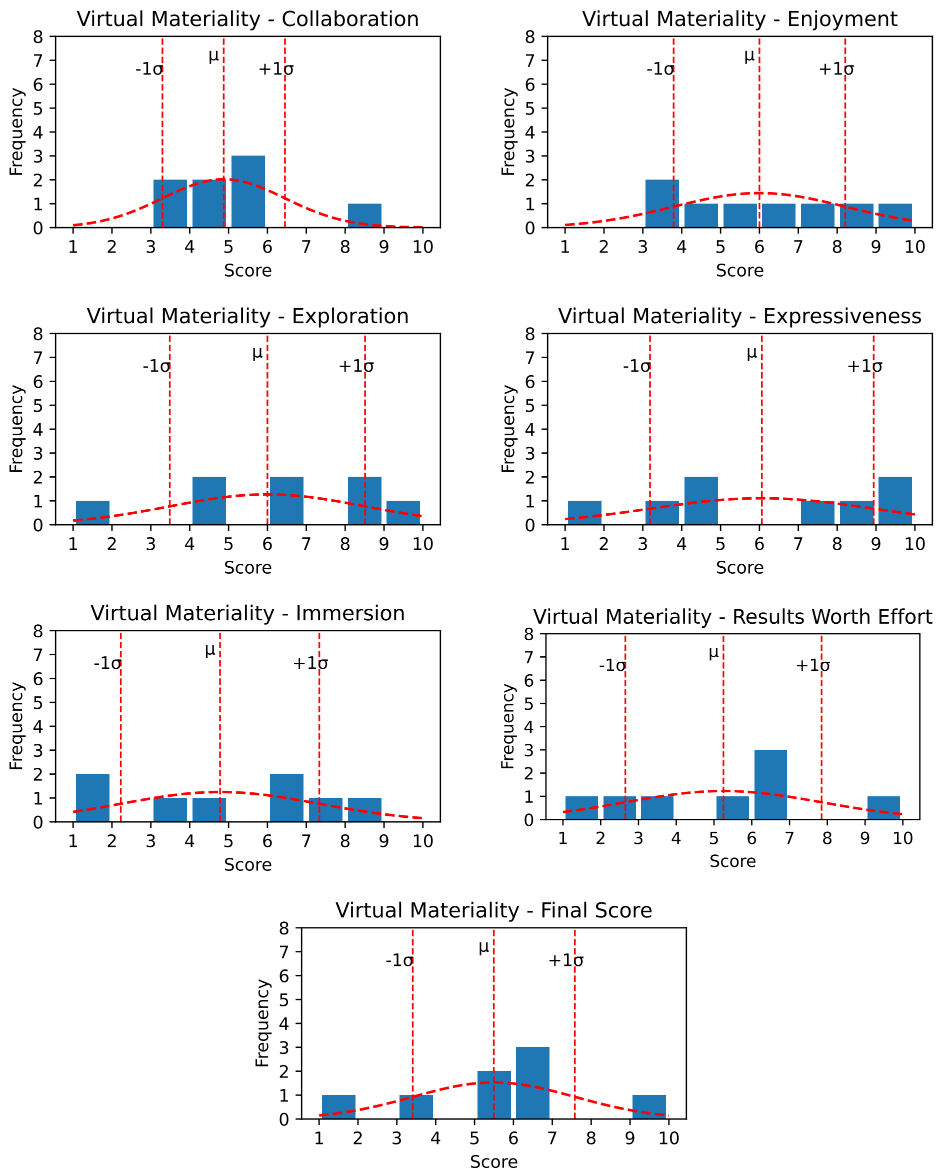



Figure 5.5: Histograms of Virtual Materiality CSI Factor scores. These generally appear to have the flattest distributions and lowest means of the three methods. Mean, Standard Deviation, and a normal fit are shown in dotted lines.

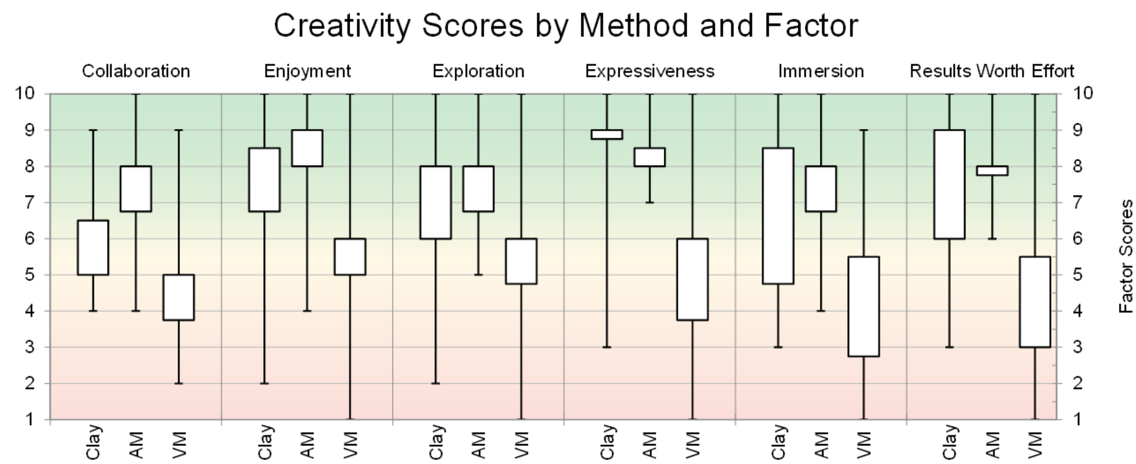



Figure 5.6: Summary of results of 96 individual Creativity Support Index questions, grouped by factor. The questionnaire contains 2 questions per factor, rated from 1-10. Find them in Fig. 4.4.

# 5.5 Quantitative Analysis of Scores

## 5.5.1 Individual Response Distribution

The results of the CSI questionnaires for each trial in each sculpting method were compiled and compared. Looking at individual responses from Fig. 5.6, we see high variance overall. This may be attributed to the fact that each question about a given factor in the questionnaire measures different aspects of that factor.

## 5.5.2 Score Distribution

The main outcome of the statistical analysis of these results is to determine how changing the sculpting method affects individual CSI questionnaire factor scores and the overall score. In order to choose the correct methods, it was necessary to test assumptions of normality and sphericity. The Shapiro-Wilks test and Mauchly's Test of Sphericity were used to determine if transformations or non-parametric analysis methods were needed. Given the results of the tests for Normality and Sphericity (Fig. 5.7, 5.8), one-tailed T-tests were performed in each direction for each pair of methods to determine which selection caused

| | Measure | Mauchly's Test of Sphericity | | | | |
|---|---|---|---|---|---|---|
| | | *w* Statistic | Chi squared | DoF | *p* Value | Result ($\alpha$ = .05) |
| All 3 Methods Within Subjects | Final Score | .504 | 4.113 | 2 | .128 | No significance |
| | Collaboration | .566 | 3.418 | 2 | .181 | No significance |
| | Enjoyment | .861 | 0.895 | 2 | .639 | No significance |
| | Exploration | .768 | 1.584 | 2 | .453 | No significance |
| | Expressiveness | .304 | 7.137 | 2 | **.028** | **Sphericity Violated** |
| | Immersion | .526 | 3.852 | 2 | .146 | No significance |
| | Results Worth Effort | .511 | 4.027 | 2 | .133 | No significance |

Figure 5.7: Summary table of Mauchly's sphericity on CSI Factor Scores and Final Score within subjects. Highlighted cells in the "Result" column indicate that Expressiveness scores within subjects violate the assumption of sphericity.

improved specific CSI scores, and their averaged Final Score. The Shapiro-Wilks test shows evidence of a non-normal distribution on 4 out of 18 sets of scores, namely Adobe Medium Enjoyment ($W = .819$, $p = .046$), Results Worth Effort ($W = .787$, $p = .021$), Polymer Clay Expressiveness ($W = .679$, $p = .001$), and Results Worth Effort ($W = .812$, $p = .038$). This can be the result of these score responses tending to hit the rating upper bound of 10/10. All results for other variables were not significant. Mauchly's test indicated sphericity is violated for Expressiveness, ($\chi^2(2) = 7.137$, $p = .028$). This may be largely due to the significantly higher variance of opinions of participants on Virtual Materiality's Expressiveness, compared to the other two methods. Mauchly's test results on other variables were not significant. Given their low number of significant outcomes, the Shapiro-Wilks and Mauchly's test results were deemed not to warrant transformations on the data, or preclude parametric tests.

| | Distribution Statistics By Factor for Each Method | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | Shapiro-Wilks Test of Normality | | |
| | Measure | Mean | Std. Dev. | Variance | *w* Statistic | *p* Value | Result ($\alpha$ = .05) |
| Adobe Medium | Final Score | 8.042 | 0.934 | 0.998 | .901 | .295 | No significance |
| | Collaboration | 7.625 | 1.474 | 2.482 | .930 | .514 | No significance |
| | Enjoyment | 8.625 | 1.615 | 2.982 | **.819** | **.046** | **Not Normal** |
| | Exploration | 7.625 | 1.192 | 1.625 | .859 | .118 | No significance |
| | Expressiveness | 8.750 | 0.829 | 0.786 | .944 | .646 | No significance |
| | Immersion | 7.438 | 1.671 | 3.192 | .933 | .547 | No significance |
| | Results Worth Effort | 8.188 | 0.827 | 0.781 | **.787** | **.021** | **Not Normal** |
| Polymer Clay | Final Score | 7.510 | 1.518 | 2.632 | .916 | .398 | No significance |
| | Collaboration | 6.500 | 1.521 | 2.643 | .944 | .656 | No significance |
| | Enjoyment | 7.438 | 2.480 | 7.031 | .827 | .055 | No significance |
| | Exploration | 7.500 | 2.077 | 4.929 | .846 | .088 | No significance |
| | Expressiveness | 8.563 | 1.810 | 3.746 | **.679** | **.001** | **Not Normal** |
| | Immersion | 7.438 | 2.627 | 7.888 | .852 | .100 | No significance |
| | Results Worth Effort | 7.625 | 1.798 | 3.696 | **.812** | **.038** | **Not Normal** |
| Virtual Materiality | Final Score | 5.495 | 2.085 | 4.968 | .937 | .581 | No significance |
| | Collaboration | 4.875 | 1.576 | 2.839 | .872 | .159 | No significance |
| | Enjoyment | 6.000 | 2.208 | 5.571 | .971 | .904 | No significance |
| | Exploration | 6.000 | 2.512 | 7.214 | .976 | .941 | No significance |
| | Expressiveness | 6.063 | 2.877 | 9.460 | .928 | .500 | No significance |
| | Immersion | 4.781 | 2.554 | 7.454 | .934 | .556 | No significance |
| | Results Worth Effort | 5.250 | 2.598 | 7.714 | .928 | .495 | No significance |

Figure 5.8: Summary table of distribution and Shapiro-Wilks test on CSI Factor Scores and Final Score for each Method. Highlighted cells in the "Result" column indicate that the assumption of normality is violated for Adobe Medium Enjoyment & Results Worth Effort, and Polymer Clay Expressiveness & Results Worth Effort.

### 5.5.3 T-test Results

Looking at the CSI score histograms for each method, (Figs. 5.3, 5.4, 5.5), it appears that Virtual Materiality scores had lower means than those of other Methods. To test for the effect of Method on CSI Factor scores and Final Score, a Python script was used to run two-tailed and one-tailed independent-sample T-tests in each direction on each pair of methods along each of the six CSI Factors and the Final Score to determine which Methods had greater score means. See Fig. 5.9 for the full results.

Independent Sample T-test Results Between Methods (A on B)

| Legend | |
|---|---|
| **Bold** | **p <= .05** |
| Highlight | 1-β >= .75 |

| | | Method B | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Polymer Clay | | | | | | | Virtual Materiality | | | | | | |
| | | Measure | Test statistic $t$ | 2-Tailed $p$ | 1-Tailed $p$ | Result ($\alpha$ = .05) | Effect size ($d$) | Power (1-β) | Measure | Test statistic $t$ | 2-Tailed $p$ | 1-Tailed $p$ | Result ($\alpha$ = .05) | Effect size ($d$) | Power (1-β) |
| Method A | Adobe Medium | Final Score | 0.789 | .443 | .222 | No significance | .413 | .195 | Final Score | 2.949 | **.011** | **.005** | **A > B** | **1.238** | **.756** |
| | | Collaboration | 1.406 | .182 | .091 | No significance | .703 | .379 | Collaboration | 3.372 | **.005** | **.002** | **A > B** | **1.339** | **.816** |
| | | Enjoyment | 1.061 | .306 | .153 | No significance | .546 | .272 | Enjoyment | 2.539 | **.024** | **.012** | **A > B** | **1.123** | **.688** |
| | | Exploration | 0.138 | .892 | .446 | No significance | .074 | .070 | Exploration | 1.546 | .144 | .072 | No significance | .764 | .424 |
| | | Expressiveness | 0.249 | .807 | .403 | No significance | .133 | .080 | Expressiveness | 2.375 | **.032** | **.016** | **A > B** | **1.072** | **.653** |
| | | Immersion | 0.000 | 1.000 | .500 | No significance | .000 | .050 | Immersion | 2.303 | **.037** | **.019** | **A > B** | **1.048** | **.636** |
| | | Results Worth Effort | 0.752 | .465 | .232 | No significance | .394 | .186 | Results Worth Effort | 2.851 | **.013** | **.006** | **A > B** | **1.212** | **.745** |
| | Polymer Clay | N/A | | | | | | | Final Score | 2.068 | .058 | **.029** | **A > B** | **.967** | **.577** |
| | | | | | | | | | Collaboration | 1.963 | .070 | **.035** | **A > B** | **.929** | **.549** |
| | | | | | | | | | Enjoyment | 1.145 | .271 | .136 | No significance | .585 | **.298** |
| | | | | | | | | | Exploration | 1.218 | .244 | .122 | No significance | .619 | **.320** |
| | | | | | | | | | Expressiveness | 1.946 | .072 | **.036** | **A > B** | **.923** | **.544** |
| | | | | | | | | | Immersion | 1.918 | .076 | **.038** | **A > B** | **.912** | **.535** |
| | | | | | | | | | Results Worth Effort | 1.989 | .067 | **.033** | **A > B** | **.939** | **.556** |

Figure 5.9: The full set of data returned by the independent-sample T-tests for each pair as Method A (row) and Method B (column) for all possibly significant results. The "Result" column indicates which of the scores had the greater mean, with greater significance bolded, and ones with greater power highlighted. Effect size is reported as Cohen's $d$ and Power $(1 - \beta)$ was computed using the G*Power software [82].

The most significant results regarded that:

- Final Score received by Adobe Medium ($M$ = 8.04, $SD$ = 0.93), when compared to scores received by Virtual Materiality ($M$ = 5.5, $SD$ = 2.09), were greater ($t(14)$ = 2.95, $p$ = .005).
- Collaboration scores received by Adobe Medium ($M$ = 7.63, $SD$ = 1.47), when compared to scores received by Virtual Materiality ($M$ = 7.63, $SD$ = 1.47), were greater ($t(14)$ = 3.37, $p$ = .002).
- Enjoyment scores received by Adobe Medium ($M$ = 8.63, $SD$ = 1.62), when compared

to scores received by Virtual Materiality ($M$ = 6.00, $SD$ = 2.21), were greater ($t(14) = 2.54$, $p$ = .012).

- Expressiveness scores received by Adobe Medium ($M$ = 8.75, $SD$ = 0.83), when compared to scores received by Virtual Materiality ($M$ = 6.06, $SD$ = 2.88), were greater ($t(14) = 2.38$, $p$ = .016).

- Immersion scores received by Adobe Medium ($M$ = 7.44, $SD$ = 1.67), when compared to scores received by Virtual Materiality ($M$ = 4.78, $SD$ = 2.25), were greater ($t(14) = 2.3$, $p$ = .019).

- Results Worth Effort scores received by Adobe Medium ($M$ = 9.19, $SD$ = 0.83), when compared to scores received by Virtual Materiality ($M$ = 5.25, $SD$ = 2.6), were greater ($t(14) = 2.85$, $p$ = .006).

There was no significant result on their Exploration scores. These results suggest that in terms of the participants' feelings of creativity, Adobe Medium and physical clay are more similar than Virtual Materiality. In fact, the means of Adobe Medium Immersion ($M$ = 7.44, $SD$ = 1.67) and Polymer Clay Immersion ($M$ = 7.44, $SD$ = 2.63) are equal. There are also fairly significant results indicating Polymer Clay scores are greater than Virtual Materiality scores on each score except Enjoyment and Indication (Fig. 5.9). These results imply that either the unique interaction features of Virtual Materiality are inefficient and un-immersive, or their implementation was not performant or feature-rich enough to be used without further development.

## 5.6 Limitations

As this is exploratory research, it was important to keep it lightweight. So, the level of detail in data gathered by these methods is rough. The questionnaire given does not capture the level of importance of each item in the Creativity Support Index. The answers are treated as evenly weighted. The trials in this study do not compare and contrast VR digital sculpting with non-VR digital sculpting. The inclusion of a fourth example program for trial, such as the desktop program Autodesk Maya was considered. It was omitted because it would have defocused the study from VR, for little benefit in the time possible to train users on it. Since the study chose to broadly compare three very different sculpting methods, it makes it difficult to draw conclusions about specific aspects of each sculpting method. For example, Virtual Materiality featured two relevant contributions: 1. A mass-conserving voxel density model, and 2. A physical tool model in a physical environment which allowed tools to be placed on shelves, gripped in different orientations, and collide with the workpiece. The study design did not isolate each one of these conditions to be able to evaluate their individual effects. In addition, comparing Virtual Materiality to Adobe Medium proved to be particularly problematic due to the gap in extra features and CPU performance optimization. Users in Adobe Medium were able to move smoothly with high variable voxel resolution, while Virtual Materiality had a lower, fixed voxel resolution and higher latency. This aspect of performance likely confounds with the interaction aspects and proved to be a larger influence than expected. During trials, users specifically mentioned differences in smoothness, glitchiness, and level of detail. Virtual Materiality also lacked audio and haptic feedback, which may have had a serious effect on usability. Finally, the greatest limitation of this research is the sample size. The diversity of participants recruited from different backgrounds and depth in observation and responses opens up a lot of questions, yet limited numbers mean the power of statistical conclusions is negligible, as evidenced in the Power columns reported in Fig. 5.9. The findings here should not be considered answers. Instead, these findings are best taken as idea-generation, and an anecdotal peek into the types of thought processes followed by users of art creation programs. Building upon these questions in future study designs unaffected by the COVID-19 pandemic and with greater resources, a sample size of 30-70 would achieve acceptable robustness. In addition, a more structured controlled scenario with specific questions may be asked to drill down more into elements of the interface design.

# Chapter 6

# Conclusions

Chapter 1 described modern sculpting programs brushes as distinctly digital, representing disembodied functions without tactile physics. This research aimed to explore digital tools which instead have more physical presence, using only consumer-level hardware. To accomplish this, an application titled Virtual Materiality was developed. Virtual Materiality uses a HMD and handheld tracked controllers in Oculus Rift S to immerse artists in a virtual studio, with virtual hands and virtual tools which all physically collide with surfaces they see. It features a clay simulation model which borrows concepts from Computational Fluid Dynamics to provide the object with the physical property of conservation of mass—a property other applications do not replicate. It also features a tool system by which users may grip tools at different points and in different orientations for leverage and range, which is not seen in other modelling programs. Statistical analysis of the CSI scores from trials between Adobe Medium, Virtual Materiality, and Polymer Clay tell us about the following hypotheses from Section 4.1:

H1: The mass-conserving voxel density model as defined in Section 3 improves user expressiveness compared to Adobe Medium's non-mass conserving voxel model.

H2: The physical tool model as defined in Section 3.4 which can be picked up, dropped, regripped in different orientations, and placed on shelves with either hand improves user immersion compared to Adobe Medium's non-physical tool model.

No evidence was found in support of these. Instead, evidence for the opposite hypotheses were found to be significant in both aspects: The mass-conserving voxel density model as defined in Section 3 may reduce both user Expressiveness and Immersion when compared to Adobe Medium. Expressiveness scores received by Adobe Medium ($M = 8.75$, $SD = 0.83$), when compared to scores received by Virtual Materiality ($M = 6.06$, $SD = 2.88$), were greater ($t(14) = 2.38$, $p = .016$). This is a result in the opposite direction of $H1_1$. Similarly, Immersion scores received by Adobe Medium ($M = 7.44$, $SD = 1.67$), when compared to scores received by Virtual Materiality ($M = 4.78$, $SD = 2.25$), were greater ($t(14) = 2.3$, $p = .019$). This is a result in the opposite direction of $H2_1$. However, due to limitations in sample size, technical limitations in Virtual Materiality, and the fact that there are many potential factors which confound the relationship, the utility of these results is low. The evidence may not conclude in a generalizable way that a mass-conserving voxel density model is inferior to a massless one as in Adobe Medium, or that a physical tool model is inferior to having a tool effect area directly attached to the hand as in Adobe Medium.

## 6.1 Discussion of Artist Experiences

Section 4.1 enumerated several questions of this research. Here are the findings related to each in turn, combining interpretation of ideas from statistical analysis, thematic analysis, observations, and discussions:

### 6.1.1 The Clay Sculpting Experience

How do artists experience sculpting with physical polymer clay? In reality, users were meditative, relaxed, connected with the physical sensations of warmth, texture, and resistance in the clay. They felt it move in their fingers and use their thumbs and palms to exert force and will on the workpiece. Contrasting this with Virtual Reality, users in VR were free, dancing, and unobstructed. Creative, but not able to feel the piece. In the absence of touch, users enjoyed feeling their own body's motion as they work. At a very high level, both experiences involve looking at the work and using it as inspiration to picture what it could be changed into. At all levels below that cognitive level, the artists' experiences with physical and digital clay were entirely different. Yet, they did not generally see one as superior or more engaging than the other, rating them fairly equally in terms of their overall effectiveness and particularly creative immersion.

### 6.1.2 The VR Sculpting Experience

How do artists experience sculpting in current VR applications? Participants clearly expressed verbally and in writing that VR was totally different from working with the clay, yet in Section 5.4 we find that Adobe Medium shared similar Creativity Support Index scores with Polymer Clay, and that Adobe Medium and Virtual Materiality bore all the significant differences, summarily that Adobe Medium's mean scores ($M = 8.04$, $SD = 0.93$) were higher than Virtual Materiality's ($M = 5.5$, $SD = 2.09$), ($t(14) = 2.95$, $p = .005$). Combining this result with themes from the observations in-session, feedback given in the qualitative open-answer questionnaire sections, and the focus group (Section 5.3), I conclude that what they have in common is not the physical or mental experience, but that they are efficient in different ways. Users in VR felt free to explore, often jumping directly to abstract shapes. Lack of fine control, combined with the speed and freedom of their unopposed hands waving controllers through the air contributed to largely focusing on sweeping movements adding or deleting material with the entire arm rather than surface detailing with the wrist or elbow. This sense of freedom was reflected in their trials and comments. The size of changes and the sound have an enormous effect on the sense of responsiveness. The ease of large changes and very small audio feedback in Adobe Medium caused their interactions to be described as 'light' and 'free', while the lack of the same simple sculpting sound in Virtual Materiality caused it to feel much less real to participants, and they rated its Immersion and Enjoyment lower. The greatest commonality between subjects was their description of VR as a different space with unique rules. One of VR's greatest uniquenesses is also its greatest complaint from participants–the lack of touch haptics compared to physical clay.

### 6.1.3 The Virtual Materiality Experience

How do artists' opinions of creativity support ability compare between Adobe Medium and the 'physical tool' interaction method presented in the Virtual Materiality prototype? In VR sculpting, users in this test converged on the most efficient ways to make larger, more kinetic expressions in their work. The 'physical tool' simulation was not the most efficient way to do that, and the flexible grip interaction was not necessarily advantageous. In the trials for Virtual Materiality, artists often gravitated toward the in-app provided Boolean CSG Tools instead of the 'physical' tools, regardless of the order they tried methods. Boolean Tools were described as 'more responsive' because they made larger changes instantly, compared to the slow pushing and resistance of the 'physical tools'. The advantage of being able to select different grips in Virtual Materiality was not realized as much as was hypothesized because in VR the users could still not feel any actual force. Although the grip location did affect the torque transferred in the simulation, users could not tell due to a lack of haptic feedback. Different grips could not communicate different haptic feedback to their hands for delicate motions, and they did not need extra leverage for large motions. The Boolean Tools in this application were allowed to be gripped differently, as the 'physical tools' were. The benefits in the change of range of motion usually afforded by different grips had some relevance here, but the Boolean Tools could be freely intersected with the workpiece without any resistance, and VR allows one to rotate their space any way they want without supporting the workpiece. This meant there were more ways to achieve desired angles and shapes. Flexible alternative gripping comes at the cost of being able to unintentionally drop tools, which users did sometimes in testing. Overall, the quantitative evaluations show that the effect of Virtual Materiality's innovations were either negative or not significant enough to overcome its lesser computing performance and feature set.

### 6.1.4 Future Directions

What are the specific needs of sculptors which are, and are not, being met by current digital sculpting methods? Where should future research into digital sculpting interactions focus its efforts? From this study's results, I identified two areas for development. 1. Haptic Response, and 2. Kinetic Response. Section 6.2 will define these.

## 6.2 Future Work

Virtual Materiality, the application, was not developed to replace any existing commercial tool. Instead, it provides artists in the study with a new reference point to prod and discover the shape of the future of digital sculpting in Virtual Reality. I can summarize findings into these main areas of improvement:

1. Haptic Response: Improve haptic experiences at the consumer level. Many issues brought up by the artists in this study are already subjects of existing control systems and haptics research. Users complained about motion sickness, lack of physical touch sensations, having to hold a controller, inability to use their palms and fingers in sculpting, etc, which are largely limitations of the computer interface. The Oculus Rift S, with its handheld controllers and lack of finger input, led to a disconnect between reality and simulated reality. Slightly newer commercial control systems, like the Valve Knuckles, attempt to solve some but not all of these disconnects. Haptic Gloves can provide finer detail inputs and outputs, yet fail to begin to penetrate into use for everyday individuals as VR controllers have. This may be due to commercial feasibility issues. It is still a current issue to develop VR and haptic hardware and haptic rendering models to improve the channels of feedback that can be provided

to artists interacting with VR. Perhaps most promisingly, it is possible to do so using Optically Simulated Haptic Feedback (OSHF) [78], leveraging the visual sense's domination over touch during conflicts of stimulus to expand a user's connection to the digital space without new hardware.

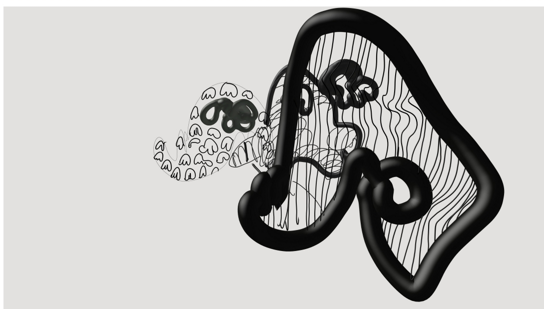
2. Kinetic Response: Improve support for the kinetic aspect of digital sculpture. Currently, VR sculpting tools focus primarily the position of the hand. The ability for VR to capture all of their body's motions is an underutilized resource. Part of this research attempted to try a more tactile experience of sculpting and discovered that this was not necessary, and in the absence of the sense of touch, even inferior. What VR contains which other media do not is the full immersion in space and full control over that space. Within the sculpting space, VR's motion tracking advantages could be applied open up doors for performance and expression to inform 3D shapes. Hand velocity can be applied to warping operations. Tossing, punching, chopping, twirling. These motions using the arms are best applied in current Virtual Reality gear and contribute to a sense of 'play' in the artistic process.

## 6.3 Final Words

Artists understand their materials on an intuitive level. A painter knows each pigment's properties, phases, quirks, and personalities. Digital artists must do the same. As much as we try to hide pixels with higher resolutions, or reframe voxel density fields as 'virtual clay', somewhere down the line, the implementation shows through. Artistic processes involve a diverse mix of thinking, intuition, play, and experimentation. While constraint is a familiar friend of artists, rigidity is their bane. We pursue digital tools that better support human intuition, lower barriers to entry, and expand exploration potential while still reaping the benefits of digital art that make it pervasive today. By conducting a pilot study with think-aloud trials, questionnaires, and a focus group, this thesis gained a greater understanding of artistic modes of thinking and what artists need from their digital tools. Through this research, we find that while breaking down the inherent rigidity of the computer program is good for creativity, we should not hide what they truly are. Microsoft Paint should never be confused with acrylics on canvas, so despite the ‘clay’ metaphor frequently used by digital sculpting programs, their processes should never be confused with the processes for working with real clay-style materials. Digital art programs use metaphors of ‘tools’ and ‘objects’, but really deal only in data and operations. The feel of their ‘material’ is only born instantaneously at the intersection of the data and operation. Yet, this inconsistency is not a problem for artists looking to work in digital media. Fluidity in work styles and crossing media boundaries is not new to artists (see works in Fig. 6.1). As argued by de Gelder et. al. in relation to applications in psychophysics research [83]:

“*VR exerts its measurable influence more by eliciting an acceptance of the virtual world (i.e., ‘suspension of disbelief’) rather than by eliciting a true belief of the realism of the VR environment.*”

In this thesis, I find that artists’ interactions and interpretations suggest VR sculpting should be regarded as its own alternative world, with the goal of feedback being communication and connectivity with the alternative rather than replicating real-life physics. We should help artists feel connected to alternate realities with touch and Pseudo-Haptic Response for communication rather than realism. Then, we should support more expressive Kinetic Responsive to let artists express themselves through more nuanced motion. VR sculpting provides artists with a unique and immersive new medium to express their creativity in a freeform, kinetic way. By virtue of their substitution of reality, 3D VR artists can offer us explorations into natively digitally authored domains, and show us alternative possibilities. I hope this thesis served you with useful insights and inspiration about digital creativity. With awareness of our effects on the machine, and its effects on us, let us thoughtfully approach shaping the exciting future of our relationship with computers and artistic expression.



(a) Veronika Szkudlarek, VR Composition for *Forest of Misfits*, Masterpiece VR, 2019.

(b) Veronika Szkudlarek, VR Composition for *Bodiez Without Organs*, Masterpiece VR, 2019.

(c) Veronika Szkudlarek, Detail of *Study for Forest of Misfits*, Pastel on Paper, 45cm × 60 cm, 2019.

(d) Veronika Szkudlarek, *Bodiez Without Organs*, Oil on Canvas, 60cm × 90cm, 2019.

Figure 6.1: An exemplar of the storied and ongoing dialogue between computer and culture. Veronika Szkudlarek's works often transcribe an idea across realities and materials: in digital VR space and in physical space.

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# Appendices

# Appendix A

# COVID-19 Procedures

Parts of the study design followed specifically to offset risks of COVID-19 during the study.

# Special COVID-19 Measures

Due to the COVID-19 pandemic, bringing participants indoors to use the VR system bears a risk of promoting spread. The strategies to mitigate this spread and its effects are as follows:

1. There will not be more than 20 total participants included in the study
2. All participants and researchers must observe physical distancing and mask-wearing rules
3. Each participant will perform their tests one at a time, with no more than one in the testing room at any time
4. Before and after each individual trial of the in-person PART A of the study, all interfaces and surrounding high-touch surfaces will be wiped down with disinfectant wipes
5. All researchers and participants must be able to show proof of vaccination for COVID-19
6. If a participant meets on-site and then chooses to withdraw their data, the contact information of the participant will be retained for at least 14 days after withdrawal to facilitate contact tracing
7. Participants and researchers on site will be provided with gloves and hand sanitizer
8. Procedure will be adjusted to stay in accordance with Ontario Health Guidelines

Version 1 - 27 Nov, 2021

# Appendix B

# Demographics Form

Form used to gather informed consent and participant demographics.

# Evaluating Virtual Reality Sculpting - Consent & Demographics Form

Title of Research Study: Evaluating Virtual Reality Sculpting

Name of Principal Investigator (PI): Dr. Andrew Hogue

PI's contact number(s)/email(s): Andrew.Hogue@ontariotechu.ca (Supervisor)

Names(s) of Co-Investigator(s), Faculty Supervisor, Student Lead(s), etc., and contact number(s)/email(s):

-Joss Moo-Young (Student Lead/Research Coordinator):
Email: joss.mooyoung@ontariotechu.net

-Veronika Szkudlarek (Supervisor)
Email: vszkudlarek@faculty.ocadu.ca

* Indicates required question

## Introduction - What is this form?

You are invited to participate in a research study entitled "Evaluating Virtual Reality Sculpting". You are being asked to take part in a research study.

Please read this consent form carefully and feel free to ask the researcher any questions that you might have about the study. If you have any questions about your rights as a participant in this study, complaints, or adverse events, please contact the Research Ethics Office at (905) 721-8668 ext. 3693 or at researchethics@ontariotechu.ca. The form includes details on study's procedures, risks and benefits that you should know before you decide if you would like to take part. You should take as much time as you need to make your decision. You should ask the Principal Investigator (PI) or study team to explain anything that you do not understand and make sure that all of your questions have been answered before submitting this form.

Before you make your decision, feel free to share this form and talk about this study with anyone you wish including your friends and family.

Participation in this study is voluntary.

This study has been reviewed by the University of Ontario Institute of Technology (Ontario Tech University) Research Ethics Board REB # 14092 on Dec 7, 2021

Document updated 5-Oct-2022

## Safety

Section 2 of 6

Part of this study will involve testing on location face to face to use a Virtual Reality (VR) system. Due to the COVID-19 pandemic, bringing participants indoors to use the VR system bears a risk of promoting spread. In addition, when using VR systems, some people can experience motion sickness or other effects. This section contains safety information and questions to help you determine if this study is appropriate for you

COVID-19 Safety Measures

At this point in time, the risk of Omicron variant of concern in Ontario is high and the risks of further transmission, severe disease, reinfection, and breakthrough infection in Ontario is moderate with a high degree of uncertainty. The overall risk assessment may change as new evidence emerges (Public Health Ontario, December 2021). We will keep you informed on these changes.

The strategies implemented by the researcher design to mitigate this spread and its effects are as follows:
-There will not be more than 20 total participants included in the study
-All participants and researchers must observe physical distancing and mask-wearing rules wherever reasonably possible
-Each participant will perform their tests one at a time, never more than one in the testing room at a time
-Before and after each individual trial of the in-person PART A of the study, all interfaces and surrounding high-touch surfaces will be wiped down with disinfectant wipes
-All researchers and participants must be able to provide proof of vaccination to participate in the study
-If a participant meets on-site and then chooses to withdraw their data, the contact information of the participant will be retained for at least 14 days after withdrawal to facilitate contact tracing
-Procedure will be reviewed and adjusted to up-to-date with Ontario Health Guidelines

Because you are coming on campus, the following safety protocols must be followed:

- Screening,
- Use of non-medical masks or face covering while participating in the research study,
- Follow instructions provided to you with respect to arriving at the study location, including entry points, designated waiting areas and washrooms, timing of arrival,
- Hand washing,
- Precautions taking public transit or travelling to the research site,
- Physical distance (maintaining 2-meter distance from others),
- Personal Protective Equipment (PPE) provided to participants by research team

We will be collecting personal contact information that we must retain in order to follow up with you and/or conduct contact tracing if you may have been exposed to COVID-19 in coming to the research site. As a result, we cannot guarantee privacy and confidentiality of your participation in the study. We cannot guarantee anonymity, as the personal contact information does identify you as a participant. Contact information will be kept separate from data collection through the research study to allow for de-identification of the research data.

During this time, the university may request information relating to all people entering and exiting our campus. As such please be advised that it may not be possible to keep your participation in a study confidential; however, no information about the data you share with us in the study will be shared outside of the research team.

If you feel that you are in a vulnerable group with respect to COVID-19 effects (e.g. senior, immunocompromised, living with individuals that may be susceptible to COVID-19), it may be best that you do not participate in the study.

You maintain your right to withdraw from the study, including research data (if applicable). If you do withdraw, we will continue to maintain your contact information and will only give it to Public Health authorities and the University if required for contact tracing.

There may be additional risks to participating in this research during the COVID-19 pandemic that are currently unforeseen and, therefore, not listed in this consent form.

If you think you have COVID-19 symptoms or have been in close contact with someone who has it, use the Government of Ontario's COVID-19 self-assessment tool and follow the instructions it provides to seek further care. In addition, you must inform the Principal Investigator immediately for follow up.

1. You will be required to provide proof of vaccination against COVID-19 on the day of your in-person visit in the first part of the study. Does this prevent you from attending? *

   *Mark only one oval.*

   - Yes, I am either unavailable at that time, or will not have full vaccination status
   - No, this is not a problem
   - Other: ______________________

2. This study involves using a Virtual Reality head mounted display for a period of around 1 hour, with freedom for taking breaks. Do you consider yourself vulnerable to motion sickness? (i.e. do you frequently feel ill while inside a moving vehicle, playing video games, or in Virtual Reality?) *

   *Check all that apply.*

   - [ ] Yes. I always feel very ill after an hour of the above activities, and would not be comfortable doing them
   - [ ] Somewhat. I may feel ill after an hour of the above activities, but I am willing to try anyways.
   - [ ] No. I do not often experience motion sickness
   - [ ] Other: ______________________

3. Do you have a strong history of photosensitivity which prevent you from watching certain movies/videos, or playing video games? *

   *Check all that apply.*

   - [ ] Yes
   - [ ] No
   - [ ] Other: ______________________

If you answer "yes" to any of the above, then you are not eligible to participate. Please do not continue or submit this form

About This Study



## Purpose - What is the study about?

The art of sculpture has traditionally involved clay or stone, and tools held in hand used to scrape and form. Now, many 3D artists work with computer software to 'sculpt' 3D objects in programs like Maya, 3Ds Max, or Blender, either to be used in digital form or to plan real physical constructions. With advances to the capabilities and availability of immersive virtual reality, there are unique opportunities to explore new ways to interact with 3D digital sculpting. To explore these opportunities, we are putting together a diverse focus group to review existing methods and discuss the ways in which we may understand and suggest improvements to the human experience of digital sculpting.

## Procedures - What happens in this study?

PART A: INDIVIDUAL TRIALS:
The Researchers will arrange with participants to meet on an individual basis for 1-2 hours. During this time, participants will make clay sculptures in three different ways:

1. Wax-based clay commonly used in industry (MonsterClay - monstermakers.com/monster-clay/).
2. A commercial digital sculpting program in Virtual Reality, using an Oculus Rift S (Adobe Medium - adobe.com/ca/products/medium.html)
3. A prototype digital sculpting program in Virtual Reality, using an Oculus Rift S (Virtual Materiality)

During each test, the participant is to think aloud, narrating what they are thinking about their experience as they go. The purpose of these tests is not to evaluate a best or worst method, but to examine the elements of each which may be beneficial for creativity, and to generate ideas for a focus group discussion. After each test the participant will complete a short survey.

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PART B: FOCUS GROUP:
After individual trials are complete, a Focus Group meeting will be arranged for around 7-10 participants, taking into account scheduling needs. The focus group consists of a synchronous group video call together with other study participants, who have also undergone the same trials. To facilitate conversation, participants are encouraged but not required to have a camera and microphone enabled. The focus group will include short sharing of experiences in turn by each participant, followed by prompted conversation related to the experience of sculpting. Lastly, there will be space for open discussion session to share thoughts and ideas. The focus group meeting will last 2 hours.

The total active time commitment for this study, including completing this form and communicating with researchers, is expected to be about 4 hours.

## Potential Benefits

Your participation is a chance to experience new ways to make art, share thoughts with new people, meet like-minded individuals, and help inform the future of human-computer interfaces for making art.

## Potential Risks or Discomforts

You may experience discomfort from eye strain or motion sickness commonly reported when using a Virtual Reality system. If you feel sick before, during, or after using the system, please stop and let the researchers know. You may stop or take a break at any time.

## What Data will be Collected?

This form collects demographic data in order to allow the researchers to select a diverse group of participants. It also collects an e-mail address to be used to communicate with the researchers.

In addition to the data in this form, the following data will be collected during the study:

PART A: INDIVIDUAL TRIALS:
-Numerical opinion data. A short agree/disagree scale survey about each method the participant tests
-Audio/Video. Think-aloud comments will be recorded and automatically transcribed using captioning software, including timings. In VR, screen recordings of each participant's in-app view, or in the case of clay: footage of them working.
-Text. Open-ended questionnaire responses on the user experience

PART B: FOCUS GROUP:
You will be asked to share your experiences with other participants, but what and how you choose to share is entirely voluntary.
-Audio/Video/Text. A recording will be taken of the online focus group session. Voices will be automatically transcribed using captioning software, including timings. Text chat messages will also be recorded.
-Images. Digital diagrams drawn by participants to communicate their ideas during the session may be collected

## Use and Storage of Data

If you volunteer but are not selected for participation in the study, you will receive notification, and then the data in this form will be deleted. If you are selected and participate, the data in this form and all other data collected during the study will be retained in a private password-protected Ontario Tech University Google Drive for two years after the end of the study, or until you withdraw.

All information collected during this study, including your age and gender, will be kept confidential and will not be shared with anyone outside the study unless required by law. You will not be named in any reports, publications, or presentations that may come from this study

Any data to be published will be rendered unidentifiable first, such that the identities of participants cannot be determined from the publication.

## Confidentiality

Your involvement in this study is private and confidential. Your privacy shall be respected. No information about your identity will be shared or published without your permission, unless required by law. Confidentiality will be provided to the fullest extent possible by law, professional practice, and ethical codes of conduct. Please note that confidentiality cannot be guaranteed while data is in transit over the Internet.

As this is study includes a focus group session, you will be asked to interact with and share your experiences with other participants during a live virtual meeting. What and how you choose to share is entirely voluntary. You may choose to use a pseudonym (fake name). You may also choose not to enable your camera, or your microphone.

## Voluntary Participation

Your participation in this study is voluntary and you may partake in only those aspects of the study in which you feel comfortable. You may also decide not to be in this study, or to be in the study now, and then change your mind later. You may leave the study at any time without affecting your study compensation. You will be given information that is relevant to your decision to continue or withdraw from participation. Such information will need to be subsequently provided. You may refuse to answer any question you do not want to answer, or not answer an interview question by saying, ‘pass’.

## Right to Withdraw

You may withdraw from the study without consequence at any time before, during, or after the study. If you want to stop or take a break, simply ask any of the researchers. If you choose to withdraw entirely, any data collected which can be linked to your identity will be deleted. You are not required to give a reason for withdrawing from or pausing the study.

## Conflicts of Interest

Researchers have an interest in completing this study. Their interests should not influence your decision to participate in this study.

A conflict of interest is when “activities or situations place an individual or institution in a real, potential or perceived conflict between the duties or responsibilities related to research, and personal, institutional or other interests”

If, for example, you are a student of one of the researchers, there is a power dynamic between you and the researcher, which may lead to a perception of needing to answer surveys in a particular way, skewing results. The research team wishes to stress that if you are a student, that your participation/non-participation and behavior in the study WILL NOT have any effect on your grades past, present, or future.

If for any reason you feel there is a conflict of interest in this study, please either discuss it with any of the researchers, or decline this study invitation.

## Compensation

-You will receive a $50 gift card for engaging in the study
-You may need to travel at your own expense to meet for individual trials in PART A of the study
-This compensation will NOT be withheld or revoked if you choose to withdraw from the study after it begins

## Debriefing and Dissemination of Results

The results of this study are intended to contribute toward a research paper published 3-8 months after the study ends. You can email a member of the research team to get information about the results after the study.

## Participant Concerns and Reporting

By completing and submitting this consent form, you do NOT give up any of your legal rights against the investigators, sponsor or involved institutions for compensation, nor does this form relieve the investigators, sponsor or involved institutions of their legal and professional responsibilities.

If you have any questions about your rights as a participant in this study, complaints, or adverse events, please contact the Research Ethics Office at (905) 721-8668 ext. 3693 or at researchethics@ontariotechu.ca.

If you have any questions concerning the research study or experience any discomfort related to the study, please contact the researcher Joss Moo-Young at joss.mooyoung@ontariotechu.net.

## Informed Consent

By completing and submitting this consent form, you are confirming that you:
1. Have read the consent form and understand the study being described.
2. Have had an opportunity to ask questions and my questions have been answered.  I am free to ask questions about the study in the future.
3. Freely consent to participate in the research study, understanding that I may discontinue participation at any time without penalty. A copy of this Consent Form has been made available to me.

## Availability

Section 4 of 6

For the first half of the study, you will need to meet in person for 1-2 hours in Toronto, Ontario, or at Ontario Tech U campus in Oshawa, Ontario, or at a suitable alternative.

For the second half, you will meet online with other participants via video conference for 2 hours. Please indicate preferences here. If you are selected, exact timings will be worked out with you via e-mail.

4. At which site would you prefer to meet? *

*Mark only one oval.*

- Prof. Szkudlarek's Studio - [ADDRESS REDACTED]
- Ontario Tech University GAMER Research Lab - Room SIRC 4310, 40 Conlin Rd, Oshawa, ON L1G 0C5
- Either site
- Other: ______________________

5. If you have any known restrictions or preference of dates or times to meet on campus from June through October, 2022, please indicate them here. *

______________________

6. If you have any known restrictions or preference of dates or times to meet via video conference call sometime in November 2022, please indicate them here. *

______________________

## About You

Section 5 of 6

Please take the time to select the answer you feel most accurately describes you. If it is impossible to answer using one of the existing options, you may type your own answer in the "other" field.
We are looking for a wide range of people with different levels of skill and experience, so there are no 'wrong' answers.

7. What is/are your profession(s)?

______________________

8. What is your level of skill with computers? *

*Mark only one oval.*

- Novice (e.g. familiar with e-mail, word processing, browsers, video conferencing, and other common uses)
- Competent (e.g. can easily navigate different computer interfaces and programs, and understand how they work to some degree)
- Advanced (e.g. can diagnose and fix issues, can explain computer hardware and/or software systems in detail)
- Expert (e.g. professional software developer, computer scientist, IT specialist etc.)
- Do not understand/unable to answer the question
- Other: ____________________

9. What is your highest level of formal education in the visual arts? *

*Mark only one oval.*

- None
- High School/Secondary School
- College/University Undergraduate Student in Visual Arts
- Completed College/University Undergraduate Degree in Visual Arts
- College/University Graduate Student in Visual Arts
- Completed College/University Graduate Degree in Visual Arts
- Do not understand/unable to answer the question
- Other: ____________________

10. What is your level of experience in the visual arts? *

*Mark only one oval.*

- None
- Novice (e.g. less than 10 hours of practice, or a few days)
- Intermediate (e.g. more than 100 hours of practice, or 1 month)
- Advanced (e.g. more than 1,000 hours of practice, or 1 year)
- Expert (e.g. more than 10,000 hours of practice, or 10 years)
- Do not understand/unable to answer the question
- Other: ______________________

11. What is your level of experience with analog sculpture of any kind (stone, clay, papercraft, etc.)? *

*Mark only one oval.*

- None
- Novice (e.g. less than 10 hours of practice, or a few days)
- Intermediate (e.g. more than 100 hours of practice, or 1 month)
- Advanced (e.g. more than 1,000 hours of practice, or 1 year)
- Expert (e.g. more than 10,000 hours of practice, or 10 years)
- Do not understand/unable to answer the question
- Other: ______________________

12. What is your level of experience with 3D digital sculpting programs (e.g. Blender, Cinema4D, Maya, ZBrush) *

*Mark only one oval.*

- None/Never heard of it
- Novice (e.g. less than 10 hours of practice, or a few days)
- Intermediate (e.g. more than 100 hours of practice, or 1 month)
- Advanced (e.g. more than 1,000 hours of practice, or 1 year)
- Expert (e.g. more than 10,000 hours of practice, or 10 years)
- Do not understand/unable to answer the question
- Other: ______________________

13. What is your level of experience with Virtual Reality? *

*Mark only one oval.*

- None/Never heard of it
- Novice (e.g. less than 10 hours of practice, or a few days)
- Intermediate (e.g. more than 100 hours of practice, or 1 month)
- Advanced (e.g. more than 1,000 hours of practice, or 1 year)
- Expert (e.g. more than 10,000 hours of practice, or 10 years)
- Do not understand/unable to answer the question
- Other: ______________________

14. What is your level of experience with Virtual Reality Sculpting Programs? *

*Mark only one oval.*

- None/Never heard of it
- Novice (e.g. less than 10 hours of practice, or a few days)
- Intermediate (e.g. more than 100 hours of practice, or 1 month)
- Advanced (e.g. more than 1,000 hours of practice, or 1 year)
- Expert (e.g. more than 10,000 hours of practice, or 10 years)
- Do not understand/unable to answer the question
- Other: ______________________

15. What is your level of experience with Adobe Medium? *

*Mark only one oval.*

- None/Never heard of it
- Novice (e.g. less than 10 hours of practice, or a few days)
- Intermediate (e.g. more than 100 hours of practice, or 1 month)
- Advanced (e.g. more than 1,000 hours of practice, or 1 year)
- Expert (e.g. more than 10,000 hours of practice, or 10 years)
- Do not understand/unable to answer the question
- Other: ______________________

16. What gender do you identify as? *

*Mark only one oval.*

- Male
- Female
- Prefer not to say
- Other: ______________________

# Appendix C

# Participant Handout

Sheet given to each participant containing overall instructions, reminders on ethics, contact information and space for notes.

# Welcome!

Thank you for joining and welcome to the study! This is the first half, where you will try three different methods of sculpting. One wax-based clay, and two very different programs which use the Oculus Rift Virtual Reality headset to interact. While you use them, you are encouraged to speak your mind and thought process. Essentially, think aloud. Your session with each method will be recorded so we can review it later. Among other things, you may choose to pay attention to:

- How it feels to use each one down to your senses of touch, sight smell etc.
- What it makes you think about
- How this tool affects or informs your process of creating or expressing

After trying each method, you will answer a short questionnaire about it regarding its ability to support creativity. There are no wrong moves or wrong answers in this study. You are not “supposed” to do anything in particular other than try these methods out and discuss what you are thinking. This research is about simply gathering your thoughts and opinions.
For your participation in the research, you receive a $50 gift card.

# Group Session

At a later date, you will meet via video call to discuss with the other participants about your experiences here, to help us gain new insights on what developers can do to make the experience of digital sculpting more powerful, more natural, and overall better. Please take notes on your experience now as it is fresh in your mind so that it may be easier to recall them l

# Reminder: What is this study?

Currently, many 3D artists work with computer software to 'sculpt' 3D objects in programs like Maya, 3Ds Max, or Blender, either to be used in digital form or to plan real physical constructions. With advances to the capabilities and availability of immersive virtual reality, there are unique opportunities to explore new ways to interact with 3D digital sculpting. To explore these opportunities, we are putting together a diverse focus group to review existing methods and discuss the ways in which we may understand and suggest improvements to the human experience of digital sculpting.

# Reminder: Voluntary Participation

All of your participation in this research is entirely voluntary. You can stop at any time without any negative consequences, which also means you keep your compensation. If you choose to quit, any data collected will be destroyed immediately. We will still hold onto your contact information for 2 weeks to support COVID-19 contact tracing. After that it too will be destroyed.

# Contact Info

This is an academic study by researchers at Ontario Tech University and OCAD University, funded by the Natural Sciences and Engineering Research Council of Canada (NSERC).

-Joss Moo-Young (Student Lead/Research Coordinator):

Email: joss.mooyoung@ontariotechu.net

-Veronika Szkudlarek (Supervisor)
Email: vszkudlarek@faculty.ocadu.ca

**-**Dr. Andrew Hogue (Supervisor, Principal Investigator)
Email: Andrew.Hogue@ontariotechu.ca

This study has been reviewed by the University of Ontario Institute of Technology (Ontario Tech University) Research Ethics Board REB # 14092 on Dec 7, 2021. If you have any questions about your rights as a participant in this study, complaints, or adverse events, please contact the Research Ethics Office at (905) 721-8668 ext. 3693 or at researchethics@ontariotechu.ca.

# Personal Notes

(e.g. personal reminders, or thoughts, questions, & suggestions that you want to bring up in the group session)

# Appendix D

# Individual Trial Script

Script and procedure used in in-person trials.

# Individual Trials Script

This is a verbal guide to be used in conversation when the student researcher (Joss) meets with the participant for them to conduct trials in person, on their own.

The researcher should arrange a time to meet the participant which is convenient and minimizes contact with other people.

**1. Greeting/Introduction:**

Hello! I'm Joss, I'm a master's student conducting this research about virtual sculpting. Thanks again for volunteering to participate today. How are you?

[A minute or so of good old Canadian small talk--probably about the weather and how cold it is]

**2. Objective & Procedure**

So, to remind you of the purpose of this meeting: this is the first half of the study, where I want you to try three different methods of sculpting. One wax-based clay, and two very different programs which use the Oculus Rift Virtual Reality headset to interact. [Researcher points out the clay, and the Virtual Reality headset]. While you use them, you are encouraged to speak your mind and thought process. Essentially, think aloud. Your session with each method will be recorded so we can review it later.

After trying each method, you will answer a short questionnaire about it.

After today comes the second half of the study. You will meet via video call to discuss with the other participants about your experiences here, to help us gain new insights on what developers can do to make the experience of digital sculpting more powerful, more natural, and overall better. That's it! This research is basically all about gathering your opinions.

For your participation in the research overall, you receive a $50 gift card. It's yours. I just need you to sign this receipt that you got it.

[Give participant the receipt to sign]

[Give participant their participation compensation gift card]

**3. Rights/Consent**

Please let me remind you, all of your participation in this research is entirely voluntary. You can stop at any time without any negative consequences. If you choose to quit, any data collected will be destroyed immediately. We will still hold onto your contact information for 2 weeks to support COVID-19 contact tracing. After that it too will be destroyed. But, you keep your gift card.

So, are you ready to get started?

[Await response from participant]

Great! Let’s get you started with our first test

**4. Tool Familiarization**

[VR: At the first time the participant must use the VR headset, they must be familiarized with the space and controls. Based on the participant’s responses to the initial demographic survey about experience with VR, the researcher can adjust their explanations]

Here are your controllers. You hold these in your hands like so. These buttons, labeled a,b, x, and y control your thumb. There’s also a stick here. There’s a trigger button for your index finger, and a grip button for the remaining three fingers (middle, ring, and pinky)

1. Controller Buttons

**5. Trials (Order of three trials may be swapped)**

[Clay Trial]

[Present participant with the post-trial survey (Appendix 5)

[Adobe Medium Trial]

[Present participant with the post-trial survey (Appendix 5)

[Virtual Materiality Trial]

[Present participant with the post-trial survey (Appendix 5)

**6. Closing**

Okay, we've reached the end of the session. Thanks for coming in and offering your thoughts! You've done a good thing here.

If you have other things to add, feel free to write them down to bring up later in the focus group. During that time you'll get to share with other participants about your experiences. Is the scheduled conference call time still good for you?

[Remind participant of the scheduled timing]

If you want to reach me for any reason, just shoot me an email.
Looking forward to seeing you again online! Have a safe trip home, and a great day! Bye!

# Appendix E

# Post-Trial Survey

Form completed by participants once for each sculpting method.

# Evaluating Virtual Reality Sculpting - PART A: Individual Trials - Post-Trial Survey

Please answer all questions on this form to the best of your ability. You may choose to refuse any question you do not want to answer. Please double-check before submitting to ensure you answered all the questions which you meant to answer.

Thank you,

Research Team
-Joss Moo-Young (Student Lead/Research Coordinator, Point of contact):
Email: joss.mooyoung@ontariotechu.net

-Dr. Andrew Hogue (Principal Investigator, Supervisor)
Email: Andrew.Hogue@ontariotechu.ca

-Veronika Szkudlarek (Supervisor)
Email: vszkudlarek@faculty.ocadu.ca

## Reminder: Right to Withdraw

You may withdraw from the study without consequence at any time before, during, or after the study. If you want to stop or take a break, simply ask any of the researchers. If you choose to withdraw entirely, any data collected which can be linked to your identity will be deleted. You are not required to give a reason for withdrawing from or pausing the study.

Document updated 27-Nov-2021

1. Which method did you just use?

   *Mark only one oval.*

   - Polymer Clay
   - Adobe Medium
   - Prototype Program (Virtual Materiality)

2. Your name

   ____________________________

## Creativity Support Questionnaire

Please rate your agreement to the following statements:

3. The system or tool allowed other people to work with me easily.

*Mark only one oval.*

| | Highly Disagree |
|---|---|
| 1 | ◯ |
| 2 | ◯ |
| 3 | ◯ |
| 4 | ◯ |
| 5 | ◯ |
| 6 | ◯ |
| 7 | ◯ |
| 8 | ◯ |
| 9 | ◯ |
| 10 | ◯ |
| | Highly Agree |

4. It was really easy to share ideas and designs with other people inside this system or tool

*Mark only one oval.*

Highly Disagree

1 ⬭

2 ⬭

3 ⬭

4 ⬭

5 ⬭

6 ⬭

7 ⬭

8 ⬭

9 ⬭

10 ⬭

Highly Agree

5. I would be happy to use this system or tool on a regular basis

*Mark only one oval.*

Highly Disagree

1 ◯

2 ◯

3 ◯

4 ◯

5 ◯

6 ◯

7 ◯

8 ◯

9 ◯

10 ◯

Highly Agree

6. I enjoyed using the system or tool.

*Mark only one oval.*

| Highly Disagree |
|---|
| 1 ⬭ |
| 2 ⬭ |
| 3 ⬭ |
| 4 ⬭ |
| 5 ⬭ |
| 6 ⬭ |
| 7 ⬭ |
| 8 ⬭ |
| 9 ⬭ |
| 10 ⬭ |
| Highly Agree |

7. It was easy for me to explore many different ideas, options, designs, or outcomes, using this system or tool.

*Mark only one oval.*

| Highly Disagree |
|---|
| 1 ◯ |
| 2 ◯ |
| 3 ◯ |
| 4 ◯ |
| 5 ◯ |
| 6 ◯ |
| 7 ◯ |
| 8 ◯ |
| 9 ◯ |
| 10 ◯ |
| Highly Agree |

8. The system or tool was helpful in allowing me to track different ideas, outcomes, or possibilities.

*Mark only one oval.*

| | |
|---|---|
| | Highly Disagree |
| 1 | ⬭ |
| 2 | ⬭ |
| 3 | ⬭ |
| 4 | ⬭ |
| 5 | ⬭ |
| 6 | ⬭ |
| 7 | ⬭ |
| 8 | ⬭ |
| 9 | ⬭ |
| 10 | ⬭ |
| | Highly Agree |

9. I was able to be very creative while doing the activity inside this system or tool.

*Mark only one oval.*

Highly Disagree

1 ◯

2 ◯

3 ◯

4 ◯

5 ◯

6 ◯

7 ◯

8 ◯

9 ◯

10 ◯

Highly Agree

10. The system or tool allowed me to be very expressive.

*Mark only one oval.*

| Highly Disagree |
|---|
| 1 ⬭ |
| 2 ⬭ |
| 3 ⬭ |
| 4 ⬭ |
| 5 ⬭ |
| 6 ⬭ |
| 7 ⬭ |
| 8 ⬭ |
| 9 ⬭ |
| 10 ⬭ |
| Highly Agree |

11. My attention was fully tuned to the activity, and I forgot about the system or tool that I was using.

*Mark only one oval.*

Highly Disagree

1 ⬭

2 ⬭

3 ⬭

4 ⬭

5 ⬭

6 ⬭

7 ⬭

8 ⬭

9 ⬭

10 ⬭

Highly Agree

12. I became so absorbed in the activity that I forgot about the system or tool that I was using.

*Mark only one oval.*

| | |
|---|---|
| | Highly Disagree |
| 1 | ◯ |
| 2 | ◯ |
| 3 | ◯ |
| 4 | ◯ |
| 5 | ◯ |
| 6 | ◯ |
| 7 | ◯ |
| 8 | ◯ |
| 9 | ◯ |
| 10 | ◯ |
| | Highly Agree |

13. I became so absorbed in the activity that I forgot about the system or tool that I was using.

*Mark only one oval.*

Highly Disagree

1 ⬭

2 ⬭

3 ⬭

4 ⬭

5 ⬭

6 ⬭

7 ⬭

8 ⬭

9 ⬭

10 ⬭

Highly Agree

14. I was satisfied with what I got out of the system or tool.

*Mark only one oval.*

| | Highly Disagree |
|---|---|
| 1 | ◯ |
| 2 | ◯ |
| 3 | ◯ |
| 4 | ◯ |
| 5 | ◯ |
| 6 | ◯ |
| 7 | ◯ |
| 8 | ◯ |
| 9 | ◯ |
| 10 | ◯ |
| | Highly Agree |

15. What I was able to produce was worth the effort I had to exert to produce it.

*Mark only one oval.*

Highly Disagree

1 ◯

2 ◯

3 ◯

4 ◯

5 ◯

6 ◯

7 ◯

8 ◯

9 ◯

10 ◯

Highly Agree

## Experience summary (Open Answer)

Describe, in words, how you felt during the trial to help evaluate aspects of the systems which helped or hindered creativity, including the hardware.

16. Please describe your overall personal experience using this method of sculpting.

17. Specify the mental experience of working with this method of sculpting. What were you thinking about?

18. Specify the physical sensation of working with this method of sculpting. For example, how do your hands physically feel holding the tools or controller?

# Appendix F

# Focus Group Script

Script and procedure used in online focus group conference call.

# Focus Group Script

**1. Greeting/Introduction:**
Hello everyone, and thanks for coming! My name is Joss Moo-Young, this focus group session is part of an academic study for my Master's thesis. I'm looking forward to hearing your thoughts!

**2. Rights/Consent Reminder**

Video, audio, and text chat in this session will be recorded and transcribed so we don't miss anything. Aside from the other participants here and the research team, your participation in this study will always remain private and confidential. Useful statements made here may be quoted or paraphrased anonymously in the resulting publication.

As always, you may withdraw from the study without consequence at any time before, during, or after the study. If you want to stop or take a break, simply ask any of the researchers. If you choose to withdraw entirely, any data collected which can be linked to your identity will be deleted. You are not required to give a reason for withdrawing from or pausing the study.

**3. Objective**

You are here to discuss your opinions, attitudes, feelings, and ideas. The goal is to examine these sculpting methods, what we like about them, what we don't, and generate some new ideas.

**4. Discussion Format**

This session will be 2 hours long and consist of 3 parts. First, each person will share a short 2-3 minute summary of their thoughts. Then we will have a guided discussion where I will ask questions I have noted here. After that, we'll have an open session so you can continue to share ideas and build on each other's thoughts. If you need to take a bathroom break or grab some tea or anything, please go ahead.

I encourage you to take notes of your thoughts, or the thoughts of others you found interesting. That way, if you have something to say but don't get the chance, you will have notes to help express yourself later.

**5. Discussion Rules**

There are a few more things you need to know about this discussion:

- The confidentiality of the discussion is important because we want to create an honest, open, non-judgemental discussion without fear of consequence. Always speak your mind even if it might be in conflict with something others have said, including me.
- We want to ensure everyone's voice has weight regardless of their credentials and level of expertise in a topic. You don't always have to say something if you don't want to, but know that we value everyone's thoughts.

- Only one person may speak at a time. If you want to speak next, you can raise your hand or finger.
- Avoid sharing ideas to each other on the side while someone else is speaking.
- When it's your turn please speak up so that the recording is smooth.
- You can use the **Google JamBoard** to help express your ideas
- I have your survey responses as well, so I can show you your own to help jog your memory if you like. I also have screen recordings of your play session. If you would like me to show parts of your session to help convey your ideas, just ask.

Is anyone unsure about what I just said?

If you have any further questions for me, please don't hesitate to ask.

**6. Presentations (40-60min)**

Alright, time to get talking. Let's go clockwise, sharing our experiences with the previous tests. I'm here to make observations, and I will also work to keep us on schedule, but otherwise the floor is yours. Feel free to jump right in and ask each other questions.

**7. Guided Discussion Questions (30-40min)**

Now it's time for the guided discussion section. I'm going to offer some prompts to get you sharing, then you build on each other's conversation.

1. With regards to their ability to help you be creative, what are the best aspects of each method you tried?
2. With regards to their ability to help you be creative, what are the worst aspects of each method you tried?
3. Who, if anyone, do you imagine using Adobe Medium specifically?
4. Who, if anyone, do you imagine using Virtual Materiality specifically?
5. If you would start using one of these VR programs, then what would you use it for?
6. If you would NOT start using one of these VR programs, then why not? What would need to change in order for you to consider using it?
7. After using these 3 different methods -- clay, Medium, and Virtual Materiality, is there anything you would like to change about the way that you currently work?
8. Ignoring practicality, if you could create the perfect sculpting method, what would it be like? Describe the way it would be used.
9. Question(s) tailored to results of post-trial response results
10. Question(s) based on the Guided Discussion results so far

**8. Open Discussion (10-20min)**

Now, we move into open discussion. Feel free to bring up any points you had thought of before.

**9. Conclusion**

Hi everyone!

Sadly, we have reached the end of our session. Thank you all for coming in today and sharing your thoughts! I will compile the data we collected and keep you posted on the results. The study is over. I will now stop recording and no more data is to be collected, but I will leave the chat open so you can continue discussion amongst yourselves if you choose. If you need anything please feel free to contact me at any timeThank you all for coming in today and sharing your thoughts! I will compile the data we collected and keep you posted on the results.

[Stop recording]